APPLIED ENGINEERING AND TECHNOLOGY DIRECTORATE

Flight Dynamics Analysis Branch
End of Fiscal Year 2002 Report

Written by members of the Flight Dynamics Analysis Branch

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National Aeronautics and
Space Administration

Goddard Space Flight Center
Flight Dynamics Analysis Branch/Code 572
Greenbelt, Maryland 20771

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Abstract

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 572, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2002. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including navigation, spacecraft trajectory design, attitude analysis, attitude determination and attitude control. The FDAB currently provides support for missions and technology development projects involving NASA, government, university, and private industry.

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1.0 Introduction

This is the fourth annual report produced by members of the Flight Dynamics Analysis Branch (FDAB) at the Goddard Space Flight Center (GSFC). As part of the Guidance, Navigation and Control Division (GNCD), the branch is responsible for providing analytic expertise for trajectory and attitude systems. This includes dynamics and control analyses and simulations of space vehicles. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis, navigation, attitude determination, and controls analysis. The Branch also provides the expertise to support a wide range of flight dynamics services, such as spacecraft mission design, on-orbit sensor calibration, and launch/early orbit operations. An active technology development program is maintained, with special emphasis on developing new techniques and algorithms for autonomous orbit/attitude systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are:

- Attitude and trajectory analysis and control design
- Control/structure interaction analysis
- Mission (attitude & trajectory) planning
- Estimation techniques
- Vehicle autonomy
- Constellation analysis
- Flight dynamics model development

This document follows an outline similar to one used in past annual reports. It summarizes the major activities and accomplishments performed by the FDAB in support of flight projects and technology development initiatives in Fiscal Year (FY) 2002. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year. The FDAB engineers that are involved in the various analysis activities within the branch prepared this document. Where applicable, these staff members are identified and can be contacted for additional information on their respective projects.

Among the major highlights by engineers in the FDAB during FY2002 are:

- ***Successful branch support for the launch and early operations of the Aqua spacecraft.*** As part of this support, the branch designed and implemented orbit raising maneuvers.
- ***Successful insertion of the MAP spacecraft into its operational orbit about L2.*** Branch engineers continued their support of the MAP mission that was launched in July of 2001. This supported included attitude control system monitoring and orbit maneuver computations.
- ***In-house development efforts begin for the Global Precipitation Measurement (GPM) mission and Solar Dynamic Observatory (SDO).*** With these two major in-

house spacecraft development projects, the branch will play a key role in the development of flight and ground orbit and attitude systems.

- ***Space Technology (ST)-5 completes Critical Design Review.*** FDAB engineers successfully completed this milestone with presentation of the final design for the ST-5 attitude control system and design of the orbit constellation.
- ***Patent application submitted for the "User Involved Star Identification and Attitude Estimation Technique."*** This technique for star identification was implemented in institutional branch attitude estimation software used for current and future operational missions.
- ***Goddard proposal for the ST-7 Disturbance Reduction System (DRS) selected.*** Branch members will have a key role in the development of algorithms for this technology pathfinder.
- ***TRMM spacecraft lifetime extended.*** Branch engineers continued active support of TRMM operations and analysis. The TRMM lifetime was extended 2-5 years as a result of a boosting of the orbit from 350 km to 400 km.
- ***Autocon selected as Goddard software of the year.*** This software was also runner-up in the NASA-wide competition. Used to automate orbit maneuvering for the EO-1 spacecraft, this software will be used for operational support of numerous future missions.

2.0 Flight Project Support

This section summarizes FDAB support to GSFC flight projects during FY02. For purposes of this report, these projects are classified as:

- Development Missions: Approved mission under development.
- Operational Missions: Missions that were in-flight in FY02. This includes missions that were in the final stages of development and were successfully launced in FY02 (e.g. AQUA).

Support to future mission concept studies and proposal support for missions seeking project approval are covered in section 3.

2.1 Development Missions

2.1.1 Aquarius (planned launch 2006)

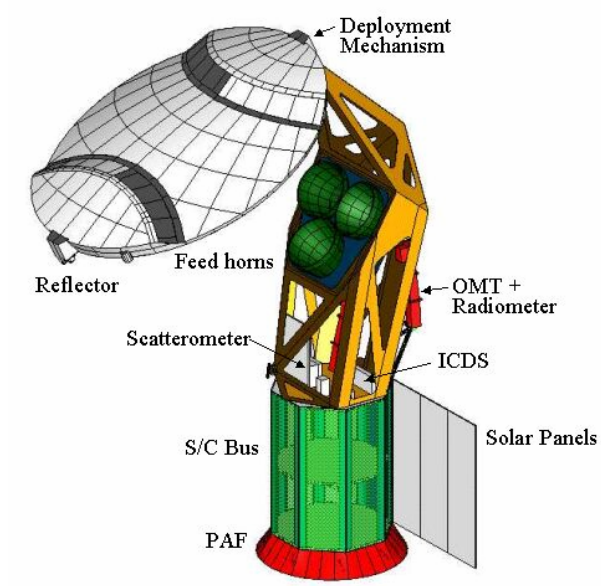

Figure 2-1. The Aquarius Spacecraft

Aquarius is a satellite that will address NASA Earth Science Enterprise questions about the global cycling of water and the response of ocean circulation to climate change. Salinity is the only surface parameter not currently measured from space. Aquarius will provide this measurement by monitoring global ocean radiometric emission, which is influenced by surface salinity.

The primary science objectives of the mission are to measure global sea surface salinity, monitor freshwater cycling at the ocean surface, understand the response of ocean circulation to buoyancy forcing, assess the impact of buoyancy forcing on the ocean thermal feedback to the climate (e.g., El Niño prediction), and improve the ability to estimate the air-sea exchange of CO2. The required mission duration is 3 years, with a goal of 5 years.

Over the past few years, the FDAB has provided a variety of analysis support for the Aquarius proposal team. The support includes assisting in the tasks of orbit selection, launch vehicle selection, devising an orbit maintenance strategy, surface coverage analysis, and evaluation of various sensor configurations. Global coverage will be achieved each week from a 600 km near-polar orbit. From this altitude, a 3-meter antenna will produce a 300 km wide swath with 100 km resolution.

The Aquarius proposal team was recently informed that their mission concept has been selected by NASA Headquarters to proceed to the formulation phase.

[Technical contact: Frank Vaughn]

2.1.2 EOS Aura (planned launch 2004)
http://eos-aura.gsfc.nasa.gov/

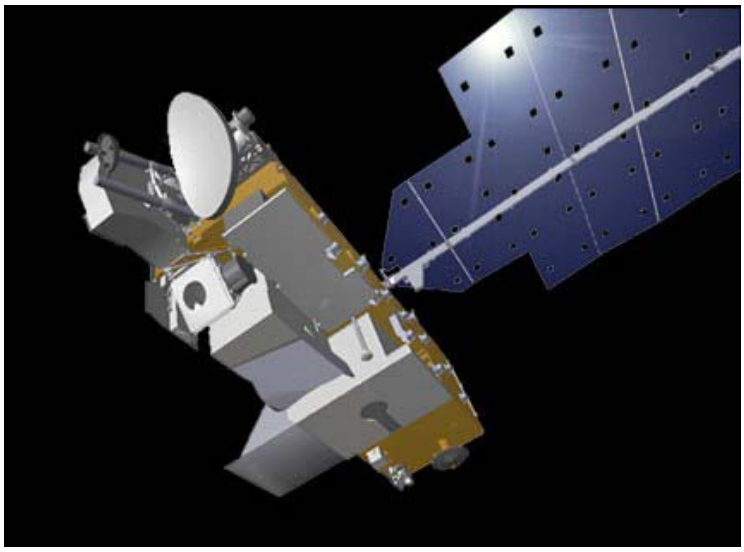

Figure 2-2. The Aura Spacecraft

The Aura mission is planned for launch in January 2004 on a Delta 7920 rocket from the Western Test Range. The planned mission lifetime is six years. The Aura mission is composed of four complementary instruments: the High Resolution Dynamic Limb Sounder (HIRDLS), the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI), and the Tropospheric Emission Spectrometer (TES).
Aura's major science objective is the study of the chemical interactions and climate change in the Earth's atmosphere, focusing on the upper troposphere and lower stratosphere. The Aura spacecraft (Figure 2-2) is 3-axis stabilized and will operate in a near-circular, sun-synchronous polar orbit at an altitude of approximately 705 km, with ascending nodal crossings at approximately 1:45 PM mean local solar time. Aura will fly in constellation with EOS Aqua (launched in May 2002) on an adjacent World Reference System (WRS) path with a given offset such that the Aqua ground track will always

intersect the Aura MLS field of view at the Earth's limb. Aura will follow Aqua with an along-track separation between 15 and 22 minutes. Figure 2-3 shows a schematic of how this is accomplished. In this example, Aqua is in an orbit with an ascending node mean local time (MLT) of 13:30; Aura will be in an orbit with MLT between 13:38 and 13:45.

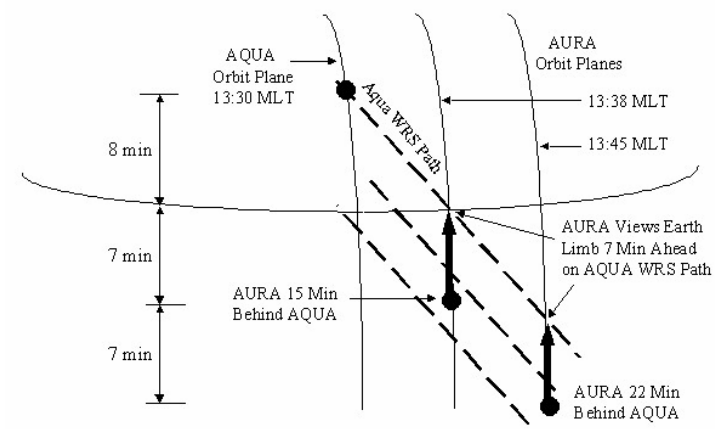

Figure 2-3. Aura Ground Track

During FY2002, the FDAB completed a preliminary ascent maneuver plan, station-keeping maneuver analysis, and constellation flying analysis including Aura, Aqua and other spacecraft. The FDAB conducted a peer review of the new COTS orbit determination system that is planned for incorporation into the Flight Dynamics System (FDS) in the Mission Operations Center (MOC). The FDAB also presented flight dynamics material at the Aura Mission Operations Working Group meeting, provided updates to the Mission Specific Requirements Document (MSRD), refined specifications for products, and completed development of draft Interface Control Documents (ICDs) with our external interfaces.

[Technical contacts: Lauri Newman, David Tracewell]

2.1.3 Global Precipitation Measurement (GPM) Mission (planned launch 2007) (http://gpm.gsfc.nasa.gov)

The Global Precipitation Measurement (GPM) mission is a follow on to the Tropical Rainfall Measuring Mission (TRMM) with the objective of covering a region of the earth up to 65 degrees in latitude while providing sufficient measurement data for short-term rainfall accumulations. The GPM plan for achieving this increased coverage is to launch a constellation of satellites, each carrying radiometers. The first of the GPM satellites, labeled the primary spacecraft, is being built as a Goddard Space Flight Center (GSFC) in-house mission in partnership with the National Space Development Agency (NASDA), the space agency of Japan. The GPM primary spacecraft is currently scheduled for launch at the end of 2007 aboard an H2A-202 launch vehicle. Its mission orbit will be at an inclination of 65 degrees and circular at 400 km. For science taking, the spacecraft will be 3-axis stabilized and earth pointing. The primary spacecraft will

carry two radiometer science instruments and a GPM Microwave Imager (GMI), and will serve to calibrate and verify the standards to be used for the constellation.

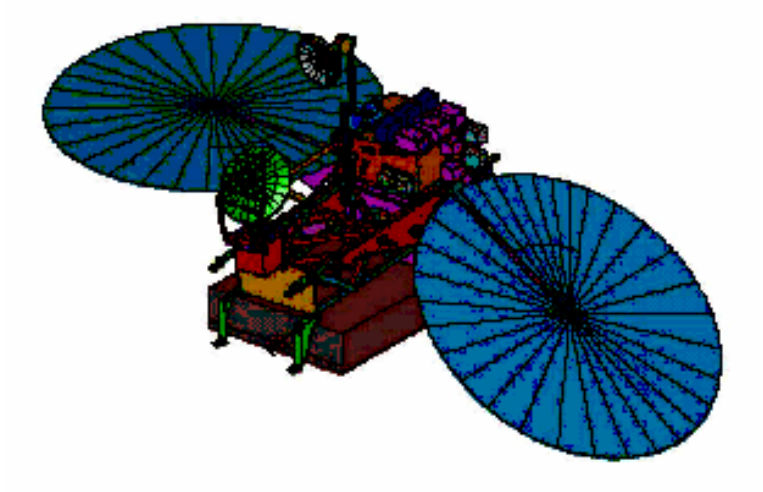

Figure 2-4. The GPM Spacecraft

The Flight Dynamics Analysis Branch (FDAB) is providing support for the GPM mission by providing orbit analysis, for both the primary spacecraft and the constellation, and attitude analysis in designing the attitude control system (ACS) for the primary spacecraft. The primary spacecraft was accepted as an in-house new start with the idea of introducing new technologies. These new technologies include those that the FDAB has provided analysis support as part of the Guidance, Navigation and Control Division (GN&CD). An important new technology is the autonomous generation of spacecraft time tagged position and velocity ephemeris using the Goddard GPS receiver, PiVoT. Another new technology flown on a previous mission is the autonomous generation of orbit maintenance commands (Autocon). Both of these new automated technologies will reduce ground operation costs significantly.

The FDAB responsibility for designing the primary spacecraft ACS began early this year. The FDAB worked with other branches and other subsystems to do trade studies to identify sensors and actuators to be used onboard. One trade study recently completed was a comprehensive look at balancing the sizing of the reaction wheels with the magnetic torquers. Each of the other sensors and actuators are undergoing evaluation at this time to determine the best complement that will meet the spacecraft's pointing and knowledge requirements for each mode of operation. New technologies being considered for the GPM primary spacecraft sensor and actuator complement, developed within the GNCD, are the Active Pixel Star tracker (APS) and a new type of reaction wheel.

The FDAB responsibility for the design of the ACS also involves the determination of modes that will take the spacecraft from separation of the launch vehicle to the earth pointing science mode. Branch attitude analysts are currently undertaking many studies to determine the transition philosophy, from mode to mode, as well as the ability of sensor and actuator configurations to meet the requirements of each mode. The most

stringent requirements are for the science mode, which requires knowledge of attitude to within 0.1 degrees, per axis, 3-sigma, and the ability to point to within 0.2 degrees per axis, 3-sigma. A trade study of error budgets for different sensor and actuator complements is currently being worked to determine which is best suited to meet these requirements. Two other requirements of concern that will affect the design of the science control laws are the necessity to do 180 degree yaw maneuvers about every month and the requirement to maintain science pointing requirements during all orbit maintenance maneuvers. Other analysis being conducted now are the design of the control algorithms for each mode, to be implemented in a high fidelity simulator and validated before becoming part of the onboard flight software.

Figure 2-4 shows the current configuration of the GPM primary spacecraft.

[Technical contacts: Joseph Garrick, Chad Mendelsohn]

2.1.4 InFocus (planned flight mid-2003)

The nine-meter InFocus Telescope pointed at high elevation during pre flight testing.

The InFocus telescope suspended below the balloon by a load train shortly after launch from Palestine, Texas (July, 2001)

Figure 2-5. InFocus Gondola and Balloon Launch

The Flight Dynamics Analysis Branch has, and continues to provide support in analysis, development, and operation of pointing systems used by the GSFC-developed InFocus X-ray Telescope. The nine-meter instrument is intended to be regularly flown on

stratospheric balloons at altitudes of 40 km. The pointing accuracy goals of the telescope range from arcminutes to an eventual goal of arcseconds. Even at stable stratospheric float altitudes, disturbances faced by the control system far exceed those experienced by a telescope in orbit. These disturbances are transmitted to a gondola via its 250 feet long load train, (the cable and parachute structure that connects it to the balloon). Much of the analysis work in the FDAB is focused on the load train dynamics and its effects on pointing performance. It is intended that knowledge gained in the development of this InFocus be shared with the entire scientific balloon community.

Two balloon flights, in August 2000 and July 2001, have been completed for the InFocus Project. The first flight, a detector test flight, carried attitude sensors on the gondola and load train but had no pointing control. These included a high accuracy gyro and several magnetometers on the gondola and along the load train. The second flight carried the completed telescope and had an azimuth/elevation control as well as gyros and magnetometers (in the gondola only). It also carried a star camera and the Pivot GPS on the telescope receiver that provided enhanced position, velocity and time information. Pivot is under development by the GNCD.

In the past year, branch efforts have been underway to analyze the data of both flights to characterize the nature of the load train disturbances and formulate improvements for the next flight expected either in May or September 2003.

These improvements are needed because of inadequate performance on the second flight. High winds at float altitude shortened the flight duration to several hours and wind gusts acting on the balloon excited the load train and gondola, leading to highly stochastic swinging motion that exceeded the capacity of the elevation control loop. Elevation and cross elevation motion also coupled into the azimuth control loop. Overall pointing errors often reached 20 arc minutes. The stochastic gyro rate signals implied that acceptable pointing for a telescope the size of InFocus, may not be feasible unless the wind speed is reduced. Future flight dates may be restricted to spring and fall periods of low-wind "turnaround".

In addition, examination of the post flight data showed that low frequency oscillations were the largest contribution to pointing error and their mitigation would substantially improve the pointing. These low frequency modes are usually associated with the entire flight configuration, i.e., balloon/load train/gondola and have characteristic periods lasting as long as one minute. High fidelity simulations were prepared in the FDAB using software capable of formulating equations of motion for complex systems, i.e., AUTOLEV. The resulting model was substituted into a Matlab Simulink control loop in order to devise solutions to the long period modes.

Even in calm conditions, swinging motions generated by control motions have plagued many balloon flights. Solutions to the problem have ranged from attempts to dampen the swing behavior to isolating the telescope instrument using gimbals etc., from the gondola base motion. One proposed approach that has been worked by the InFocus science team is to replace the azimuth/elevation control with a small spherical ball rigidly attached to

the telescope and floated on an oil-filled cup attached rigidly to the gondola base. Analysis by the FDAB showed this to be a good solution for a later flight, but not practical due to budget and schedule constraints for the next flight. For this flight, a less expensive alternative was sought. The proposed solution is to actively keep the gondola level, even if there is swinging from the balloon.

Approaches using large momentum wheels and shifting weights were studied. The results of simulations concluded that the shifting weight approach was better. Here, the horizontal location of two masses is varied to keep the center of mass aligned with the force from the load train so that its torque on the gondola is kept near zero, even though the gondola is translating through a swing motion. In this scheme, stepper motors move 60 kg weights along two horizontal tracks in proper phase with the elevation and cross elevation motion. Efforts are continuing to establish the balance-weight loop parameters.

This scheme is dependent on an accurate knowledge of the tilt of the gondola base. Because the flight software is being recomposed in XML- based software, a capability is forthcoming that will allow the use of Kalman filtering to estimate the tilt and other pertinent variables.

Also, the data suggests that there is a correlation of swinging excitations with altitude changes that occur with the occasional dropping of ballast. This could indicate a nonlinear effect for further study.

[Technical Contact: Dave Olney]

2.1.5 Solar Dynamics Observatory (SDO) (planned launch 2008)

http://lws.gsfc.nasa.gov/sdo.htm

The goal of the SDO mission is to observe the Sun's dynamics to increase understanding of the nature and sources of solar variability. The focus areas for the observations are:

* Changes in the solar magnetic field
* Relationships between the Sun's magnetic field and mass and energy releases

This past year has seen the start of the Solar Dyamics Observatory (SDO) mission. Initial design and concepts were put forward, and in the summer of 2002, an initial spacecraft concept was presented.

Flight Dynamics Analysis

As we begin to understand the requirements for developing the ground system and operational concepts for the Solar Dynamics Observatory, there are numerous mission analysis items that must be studied. The Flight Dynamics Analysis Branch at GSFC has been working many Flight Dynamics related analysis items since the spring of 2002. These include:

- A trade study to determine whether the SDO propulsion system should include a solid Apogee Kick Motor (AKM) and an auxiliary hydrazine system or consist of a restartable Liquid AKM fueled by a bipropellant propulsion system.
- The Launch and Early Orbit (L & EO) mission profile for the bipropellant system (the system of choice in the trade study) was generated including orbit maneuver placement, ground station and TDRS coverage and a timeline for Flight Dynamics operations.
- The orbital profile that permitted analysis of the amount of radiation that SDO would experience in the L & EO phase was computed.
- Mission orbit studies have also been worked in these areas: East-West station keeping, solar Radio Frequency Interference (RFI) at ground stations where science data will be dumped, and a right ascension of the ascending node trade study to help minimize orbital eclipse times and optimize High Gain Antenna gimbal angle operations.
- To aid in the gimbal angle studies, the FDAB worked with the SDO mechanical design engineers and the engineers from Analytical Graphics, Inc. to develop a computer graphics model of SDO. With this model, we were able, using AGI's Satellite Tool Kit software, to determine the time history when the SDO HGAs were obscured by a portion of the spacecraft from "seeing" a desired ground station.
- The amount of ground station tracking data that would be required for orbit determination in the mission orbit was analyzed using orbit determination error analysis.

Attitude Analysis

In August of 2002, the instrument suite was selected, and an SDO Project Kickoff Meeting was held the first week in September. The GNC attitude team has started putting together low fidelity simulations so we can start designing and modeling the control modes. Spacecraft jitter has been identified as one of the control system's tall poles, so we are working with the scientists to firm up the requirement, so we understand what we have to do. Component sizing and accuracy requirements are being worked. This includes reaction wheel momentum and torque capability, as well as thruster size and placement. In addition, nutation studies and analysis are ongoing, as this may be a large design driver, especially with a spinning upper stage to get to Geostationary Tansfer Orbit (GTO). Discussions have already occurred with the flight software group (Code 582) to scope the automatic code generation and automatic algorithm documentation tasks, as well as the amount and type of flight software testing that will be required.

The above analyses comprise only a small beginning to the work that FDAB will perform in aiding the design, testing, and operations of SDO.

[Technical contacts: Stephen Andrews, Bob DeFazio]

2.1.6 Space Technology 5 (ST-5) (planned launch 2004)
http://nmp.jpl.nasa.gov/st5/

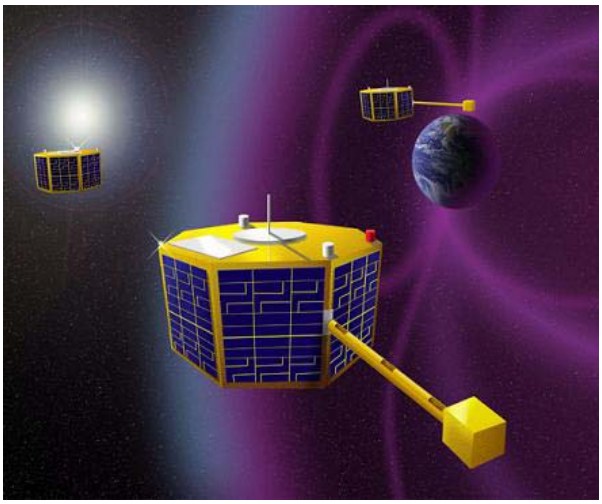

Figure 2-6. The ST5 Constellation

Space Technology 5 (ST-5) is a mission in the New Millennium Program and NASA's first experiment in the design of miniaturized satellite constellations. The mission will last 3 months. During this time, the constellation of three spin-stabilized spacecraft shown in Figure 2-6 will validate new technology for spaceflight and demonstrate science grade data acquisition from a high precision three-axis magnetometer. The new technologies include a miniature cold gas thruster, x-band transponder, lithium ion battery, variable-emissivity coatings, ultra lower-power logic, autonomous constellation management ground software, as well as, various technology improvements embedded in the spacecraft itself. In addition to validating these new technologies and instruments the mission goal is to reduce the weight, size and cost of space missions, while preserving or improving technical capabilities.

The ST-5 mission design team is designing a maneuver sequence that will validate the miniature cold gas thruster and allow for science grade magnetic field measurements. Over the last year the cross link antenna originally proposed to fly on the spacecraft has been eliminated. As a result, the proximity requirement of 1000 km at apogee has been lifted. The new requirement is to achieve a 0.5 hour Mean Local Time (MLT) separation between spacecraft in a string of pearls configuration no more than 45 days after deployment. The required configuration is shown in Figure 2-7. Limited fuel capacity dictates that the deployment of the three spacecraft must be planned as efficiently as possible to meet this new requirement. Furthermore, as a launch vehicle selection for ST-5 continues and the launch parameters remain unknown, designing a constellation scheme robust to unknown orbital parameters and compliant to the spacecraft operating constraints is crucial for mission success. The maneuver plan incorporates an orbit phasing scheme that takes advantage of small variations in the orbit periods between the spacecraft to place the spacecraft in the required configuration. The orbit phasing scheme will require that the leading and trailing spacecraft perform a 1 m/s maneuver in opposite directions along their directions of motion.

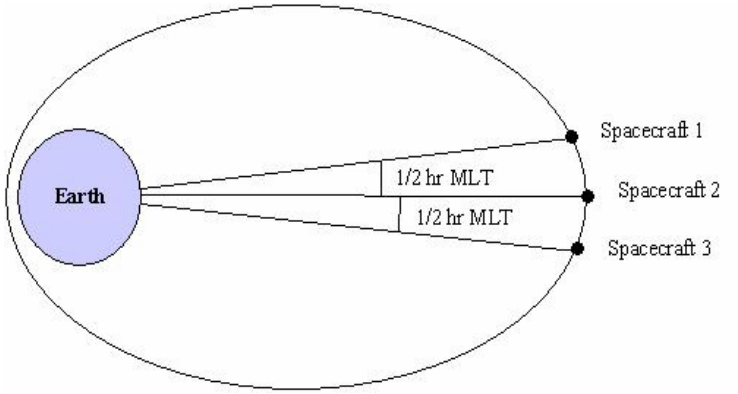

Figure 2-7. ST-5 Spacecraft Separation

The onboard ACS hardware consists of a sun sensor mounted perpendicular to the spin axis, the three-axis magnetometer, and the cold gas thruster. The challenge was to provide an ACS that uses simple algorithms to minimize onboard processing and work with the limited sensor and actuator complement. Algorithms developed for the ST-5 ACS use Rhumb line precession to keep the spacecraft spin axis aligned with the ecliptic pole and to reorient the spin axis when orbit adjust maneuvers are required. These algorithms have been tested using a hi-fidelity simulation that models the spacecraft orbital and rotational dynamics, sensors, actuators, and space environment. Passive nutation damping will be achieved using the fluid-filled ring damper shown in Figure 2-8. In the past, fluid-filled ring dampers have required a fluid reservoir to reduce the internal pressure of the damper, which increases as the fluid expands with increasing temperature. The small size of the ST-5 spacecraft has allowed a smaller fluid-filled ring damper to be designed that does not require a fluid reservoir and functions at internal pressures up to 10,000 psi. This provides simpler design, integration, testing and lower weight. The damper will be tested at NASA-GSFC by mounting the damper on the platform of a torsional pendulum and observing the damping of the platform rotational motion with rates telemetered via an RF link.

Figure 2-8. ST-5 Nutation Damper

As an experimental phase of constellation control, the ST-5 GN&C team is proposing to control the relative position of each ST-5 spacecraft thru actively controlling the ballistic properties of each spacecraft thru perigee. Small changes in each spacecraft's attitude will result in variations in the cross sectional area, thus the drag profile, experienced through atmospheric passes. These differences can be calibrated as small maneuvers to further tune the constellation's relative formation. This control scheme will be attempted at the end of the mission; after all other mission goals have been met.

[Technical contacts: Marco Concha, Jim Morrissey]

2.1.7 Space Technology-7 (ST-7) Disturbance Rejection System (DRS) (planned launch 2006)

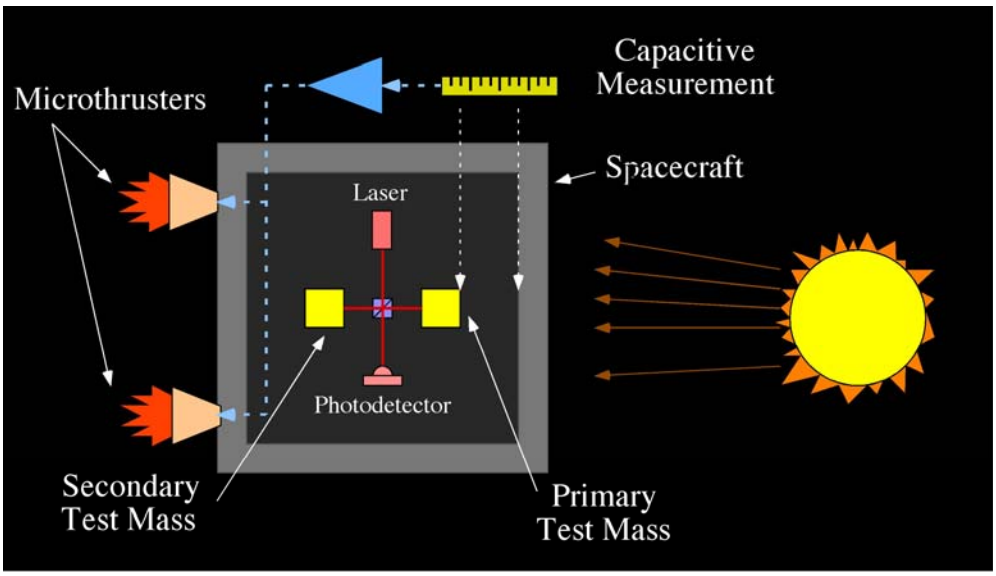

Figure 2-9. Conceptual Diagram of the ST-7 Disturbance Reduction System

Design of the ST-7 spacecraft and its experiment packages is a joint venture of ESA, JPL, NASA/GSFC, Stanford University, and Busek Co., Inc. The NASA/GSFC contribution will be dynamical modeling, controller design, and flight code generation for the ST-7 Disturbance Rejection System in the LISA Test Package. FDAB effort on the ST-7 DRS in FY2002 has focused on dynamical model development and preliminary controller design.

The ST-7 DRS will include two free-floating test masses that are shielded from solar radiation pressure. Thrusters would then be used to establish disturbance-free (usually called "drag-free") motion by moving the spacecraft to center the test masses in their respective sensor cages. Models have been created for the disturbance noise spectra of solar radiation pressure and test mass accelerations. Design requirements for the colloidal propulsion devices and appropriate thruster quantization levels have been determined. A 7-degree-of-freedom model of the dynamics of the spacecraft and two test masses—two translational DOF for each body, plus rotation of the main spacecraft—has been

developed and validated against a Simulink model. This model has both linear and nonlinear versions, and it includes star tracker attitude measurements and preliminary control algorithms for attitude control, DRS control, and Gravity Reference Sensor (GRS).

ST-7 spacecraft control requires a complex design, with two main control loops. First is the translational controller, which controls the position of the spacecraft to establish drag-free motion the first test mass. The second controller is the spacecraft attitude control, which is currently designed to orient the spacecraft inertially in the low frequency band (DC and near DC). However, it is also designed to center the spacecraft about the second test mass (establish drag-free motion about the second test mass) in the ST-7 science measurement band (1 to 10 mHz).

[Technical Contact: Scott Starin]

2.1.8 Triana

Triana is a mission dedicated to helping scientists construct more accurate models of Earth's climate and obtaining a detailed understanding of how solar radiation affects climate. Triana is designed to study the Earth, for the first time, from the vicinity of the Sun-Earth L1 Lagrange Point, a vantage point 1.5 million kilometers from Earth Sunward, and promises to offer new insights into how our planet's climate works as an integrated system. Triana will use its science instruments to meet the following science objectives:

- Make direct measurements of the radiant power emitted by the illuminated side of the Earth to increase the understanding of how much of the Sun's energy is absorbed in the atmosphere and thus improve the understanding of global climate.
- Observe the vegetation canopy structure and evolution to monitor the health of the Earth's vegetation and measure ozone and cloud coverage to study their affect on the amount of UV radiation that reaches the ground.
- Measure global aerosol optical thickness to increase our knowledge of how pollution, generated by both human and natural causes, affects the Earth.
- Improve our understanding of the characteristics of the solar wind and magnetic field and provide an early warning system for communication satellites and ground based systems susceptible to solar-related disturbances.

Triana is currently in storage, and NASA is investigating a number of launch vehicle options. Triana and its upper stage will nominally be deployed by a Space Shuttle Orbiter from low Earth orbit (LEO). From LEO the upper stage burn will increase the Triana velocity by approximately 3.1 kilometers per second sending Triana on a trajectory to the Sun-Earth L1 orbit. Approximately 6 months after the upper stage burn, the Triana propulsion system will be used to achieve the nominal L1 mission orbit. In the nominal L1 mission orbit, the Sun-Earth-Triana angle will nominally be maintained between 4.0 and 15.0 degrees for a period of 5 years. After mission orbit insertion at L1, small maneuvers will be required to maintain the Sun-Earth L1 orbit.

The Flight Dynamics Analysis Branch of the GSFC Guidance Navigation and Control Center leads the Triana flight dynamics team, which consists of NASA civil servants, Purdue University personnel, and contractor personnel. The Triana flight dynamics team is responsible for the nominal trajectory design and for providing the nominal trajectory data to the Johnson Space Center in preparation for deployment from the Space Shuttle Orbiter. The Triana flight dynamics team is responsible for the development of a trajectory correction maneuver plan, for pre-mission analysis of the trajectory correction maneuvers, for pre-mission orbit determination error analysis, for determining the required tracking schedule for the Deep Space Network (DSN) and Universal Space Network (USN) stations which will support Triana, and for contingency analysis. During the early mission phase, the Triana flight dynamics team will be responsible for generating the maneuver commands, for orbit determination, and for product generation. The Triana flight dynamics team, with support from the Mission Applications Branch, added automation functionality to Purdue University's Generator software, which greatly reduced the time required for nominal trajectory generation. In conjunction with Analytical Graphics, Inc. (AGI), the Triana flight dynamics team is developing software, which will automate the manually intensive process of determining the trajectory correction maneuver fuel requirements. The Triana flight dynamics team, in concert with the Attitude Control System (ACS) Flight Software team, completed testing and verification of the final attitude control system flight software build for delivery to the spacecraft prior to storage and completed a preliminary delivery of the attitude determination ground system. Triana flight dynamics team personnel have successfully supported Triana Project reviews including the trajectory design peer reviews.

[Technical contacts: Greg Marr, Steve Cooley, Rick Harman]

2.2 Operational Missions

2.2.1 Earth Observing System (EOS) Aqua

http://eos-aqua.gsfc.nasa.gov/

The focus for the Aqua Project is the multidisciplinary study of the Earth's Interrelated Processes (atmosphere, oceans, and land surface) and their relationship to earth system changes. The global change research emphasized with the Aqua instrument data sets include: atmospheric temperature and humidity profiles, clouds, precipitation and radiative balance; terrestrial snow and sea ice; sea surface temperature and ocean productivity; soil moisture; and the improvement of numerical weather prediction.
The Aqua spacecraft was launched May 4, 2002 on a Delta II 7920-10L rocket with 9 strap-on solid rocket motors and a 10-foot composite fairing from the Western Test Range at Vandenberg. The planned mission lifetime is six years. Aqua is the lead spacecraft in the PM portion of the EOS AM & PM constellations.

The Aqua Flight Dynamics Team (FDT) provided pre-mission analysis support, participated in the pre-mission testing/simulations, supported the spacecraft launch, and planned the ascent maneuvers to achieve the desired mission orbit. The FDT also provided post-launch attitude sensor calibration products, daily planning products, critical activity planning/monitoring, and Flight Operations Team (FOT) training during the 120-day checkout period.

The FDT planned the ascent maneuvers necessary to achieve the desired Aqua mission orbit while also phasing with the EOS AM constellation to minimize potential ground station conflicts (and possible collisions) between constituents of the two constellations. Although the two constellations reside in separate orbit planes, the intersection of the two planes occurs near the northern EOS Polar Ground Network (EPGN) sites and could have led to EPGN resource conflicts.

The FDT also provided maneuver information to the Aqua Project management and Air Force representatives from Cheyenne Mountain to assess the potential for close approaches with other spacecraft (or tracked space debris) during the ascent maneuvers. Backup maneuvers were planned by the FDT for each ascent maneuver and these were also assessed for close approaches. The timing of the later maneuvers in the ascent scenario was very critical to achieve the correct phasing with the AM constellation. Backup maneuvers were usually planned within a few orbits of the prime maneuver. The repeatability of the thruster performance during the first four of six ascent maneuvers was negatively affected by flight software (FSW) changes and altered inertia parameters implemented by the manufacturer to correct unexpected thruster duty cycle behavior. These spacecraft changes resulted in the first four FDT maneuvers not meeting their targeting goals. Once the critical spacecraft parameters were updated and used for the last two maneuvers, the FD maneuver team achieved the final orbit within several meters.

The FD attitude sensor calibration team provided parameter updates for the three-axis magnetometers (TAMs), gyros, and star trackers. The initial FDT star tracker calibration

showed a very large offset in the boresight separation (~0.2 degrees), much larger than that expected due to launch shock (typically <0.02 degrees). This apparent boresight offset was too large for the onboard star identification algorithm to work, so Fine Point Mode (FPM) transition was delayed. The large discrepancy in the star tracker boresight positions was finally traced to a sign error in a star tracker alignment matrix in the FSW and the simulator. FPM had already been achieved using the first FDT star tracker calibration (~0.02 degrees offset from nominal), but a new calibration update was required once the sign error was corrected in the FSW. The new computed offset from nominal was ~0.01 degree (~40 arcseconds). A large bias was discovered in TAM #1 by the FD calibration team. A coarse, early mission TAM-1 bias update was provided to improve attitude control in modes that use the TAM. Fine TAM calibrations were done later in the 120-day checkout phase. An error in the onboard magnetic field calculation was also identified by FD calibration team and later corrected in the FSW. Although it was only a one-character error in the FSW code, the resulting error in the onboard reference field and associated attitude was quite significant. Earth sensor calibration parameters were not uplinked since the noise on the sensor was greater than the potential corrections.

The FDT provided significant assistance to the FOT when investigating several anomalous transitions from FPM to one of the spacecraft safe modes—Earth Point Mode (EPM) or Sun Point Mode (SPM). The FDT provided specific analytical results, FD product interpretation, and technical support for numerous meetings. The FDT also provided daily planning products, routine attitude support, and trained the FOT in the operation of the FD System (FDS) for the duration of the mission. The transition to Aqua FOT routine operation support was completed on 9/30/02.

[Technical contact: David Tracewell]

2.2.2 Earth Observing System (EOS) Terra

http://terra.nasa.gov/

Terra has been on orbit since December 1999 and is operating nominally. In FY2002, the FDAB supported the Earth Science Mission Operations (ESMO) Project in planning for a Terra Deep Space Calibration (DSC) attitude maneuver. The purpose of the DSC is to provide the science instruments with calibration opportunities using the cold background of deep space and the stable lunar surface. Baseline DSC maneuver is a constant rate (Y-axis) pitch maneuver with an inertial 0.122 degree/sec rate. DSC is initiated at the sub-satellite point of the Earth surface terminator, and is completed before spacecraft day, as shown in Figure 2-10.

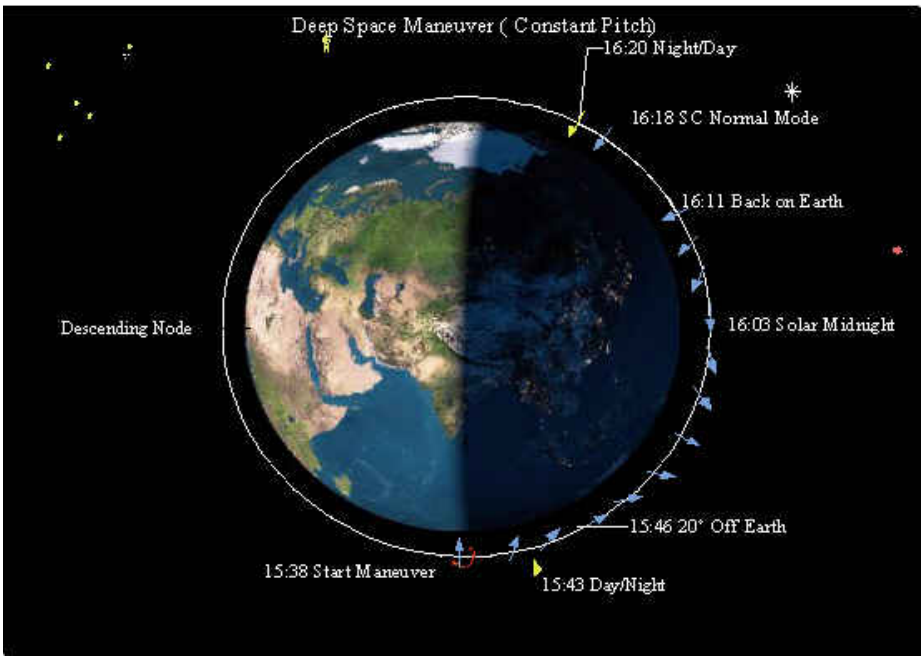

Figure 2-10 Terra DSC Timeline

Figure 2-11 illustrates the Earth-Moon geometry for Terra DSC maneuvers, as Viewed from the North celestial pole. For the DSC maneuvers *without* lunar viewing, the Moon must be between last quarter and first quarter phase to avoid potential impingement of reflected sunlight from the moon into MODIS or the other instruments. For the DSC maneuver *with* lunar viewing, the maneuver is to be executed ~2 days before full moon with a lunar phase angle of ~22.5 degrees (specific time depends upon exact Descending Node crossing time.)

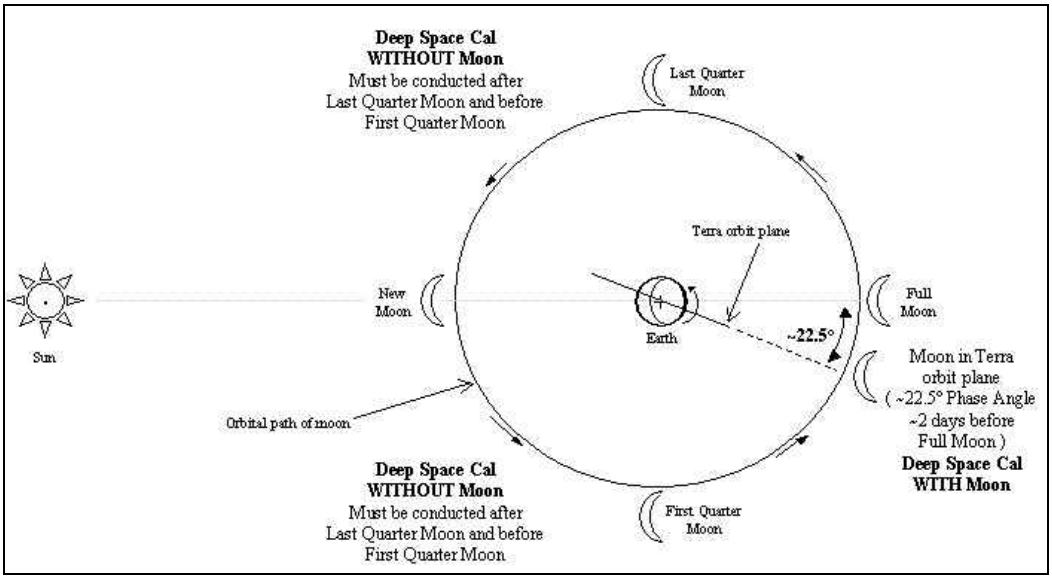

Figure 2-11 Terra DSC Geometry

ESMO personnel presented a briefing of an integrated plan for Terra and Aqua Deep Space Calibration to NASA HQ on August 28, 2002. The presentation was received very favorably, and subsequently, Code Y asked Code Q to provide an assessment of the maneuver and its associated risks. To enable Code Q to comply with the Code Y request, the ESMO Project is responsible for implementing a review and is requesting GSFC Code 300 support in this endeavor. The review panel will include FDAB personnel. The FDAB will also be involved with the actual DSC maneuver planning, maneuver simulations and validation, and maneuver execution.

[Technical Contact: Mark Woodard]

2.2.3 Earth Radiation Budget Satellite (ERBS) Decommission

The Earth Radiation Budget Satellite (ERBS) mission was intended to be a 2-year mission; eighteen years after it's 1984 launch it is still operating and producing useful science data. While ERBS continues to collect science data with the SAGE II and ERBE instruments, the technology is more than 20 years old and much more sophisticated and accurate instruments are available. In the summer of 2002, the NASA HQ Earth Science Program Office decided to decommission the ERBS satellite to ensure funding for future missions and more up-to-date and functional Earth science missions. The GSFC ERBS Mission Manager Vickie Moran was tasked to produce a decommission plan for the ERBS satellite which maximized the safe disposal of the satellite while meeting science and budget constraints. In a remarkably short amount of time, Vickie and her team, which included 572 branch members Frank Vaughn, Sue Hoge and Jim Morrissey, were able to produce a viable ERBS Decommission Plan that NASA HQ approved on June 20, 2002. Per NASA directive, a Peer Review of the Decommission Plan was held on July 8th; the Peer Panel included Karen Richon (chair), Dave Mangus and Greg Marr of 572. The Panel was impressed with the work the team had produced in such a short time and approved the plan.

The primary goal of the Decommission Plan was to lower the perigee altitude as much as possible so that the ERBS orbit decayed more quickly, decreasing the predicted lifetime from 18 to 9 years (nominal predicted lifetime). A secondary but important goal was to complete all maneuvers by the end of Fiscal Year 2002. Hardware constraints limited the duration and number of maneuvers which could be performed from July 14-Sept 30 to 34 maneuvers, leaving fuel in the tanks, so the plan was to empty the tanks after the last maneuver on Sept 30.

[Technical Contact: Sue Hoge, Frank Vaughn]

2.2.4 The Far Ultraviolet Spectroscopic Explorer (FUSE)
http://fuse.pha.jhu.edu/overview/mission_ov.html

FUSE is part of the NASA Origins Program. The purpose of the Origins Program is to answer two fundamental questions: Where do we come from? Are we alone? FUSE gives

astronomers the unique capability of observing the universe's far ultraviolet portion of the electromagnetic spectrum (approximately 90 to 120 nanometers). Studying this light, astronomers are able to better understand the conditions just after the big bang, as well as the chemical evolution of galaxies and interstellar gas clouds.

In the fall of 2001, the FUSE spacecraft lost two reaction wheels. In May 2001, one gyro failed. Based on intensity warnings, it is anticipated that all of the remaining gyros will also fail. With the mission in jeopardy, the Johns Hopkins University Applied Physics Laboratory (JHUAPL) and Orbital Sciences Corporation (OSC) requested the FDAB to review the recovery procedures, attitude determination methods, and control system designs. Working closely with OSC, the FDAB studied various attitude and rate determination methods to determine the best fit for the mission in the event of gyroless operations. The FDAB also developed a simple safe-hold design that will maintain a power-positive attitude in the event that attitude determination and all of the gyros are lost.

Two attitude and rate determination approaches were tested. One relies on a kinematics model for propagation—a method used in aircraft tracking—and the other is a traditional extended Kalman filter (EKF) that utilizes Euler's equations in the propagation of the estimated rate. Both methods compare the measured geomagnetic field with an onboard model of the expected magnetic field to update the attitude and rate estimates. No other attitude sensors are used. The traditional EKF was selected by OSC for gyroless operations, primarily since the flight software is currently running an EKF. The attitude and rate estimates must be within 2 degrees and 20 arcsec/sec, respectively, for the star sensor to locate target stars for science operations. Whether or not the system will remain stable in a closed-loop sense during slew maneuvers is still under investigation.

The new safe-hold algorithm is required to point the solar arrays at the Sun during the daylight portion of the orbit and hold the instrument out of the orbit plane without the use of gyros. The algorithm makes use of a physical consequence of "B-dot control," which simply controls according to the difference between consecutive magnetic field measurements. If B-dot control is applied to a body that has an internal momentum, that momentum will tend to precess away from the orbit plane. By controlling a wheel with its axis parallel to the instrument to hold the wheel at near constant speed (providing internal momentum), the wheel and instrument are made to precess away from the orbit plane. The wheel is then slightly modulated to maintain Sun pointing.

During this development effort, the FUSE spacecraft has continued to perform world-class science. Some of the discoveries have been a galactic corona that is much larger than expected and the discovery of hydrogen on Mars. The "Science Summaries" section at the web site has a list of highlights.

[Technical contacts: Dave Mangus, Julie Thienel, Rick Harman]

2.2.5 Geostationary Operational Environmental Satellite – N (GOES-N)

In a program stretching back for more than twenty-five years, GOES-N will be the first satellite in the fourth series of NOAA geostationary equatorial weather satellites. Built by Boeing Satellite Systems (BSS), El Segundo, CA, this spacecraft is scheduled for launch in the first quarter of calendar 2004. Unlike the earlier series, the Flight Dynamics analysis and operations are not under the direct control of Goddard's Flight Dynamics Analysis Branch (FDAB) and its predecessors. Instead, the FDAB is serving as a consultant to the GSFC GOES Project in reviewing BSS Flight Dynamics mission analysis and operational planning. The GOES-(N-Q) contract specified that these spacecraft be delivered to their checkout longitude with BSS performing and responsible for all Launch and Early Orbit (L&EO) operations. This is still the case; however, a recent proposal by BSS would include GSFC Flight Dynamics personnel on the BSS Flight Dynamics team for L&EO. Training of these GSFC personnel will begin in early spring 2003.

GOES-N will be launched on a Delta-III rocket from Kennedy Space Center into a very eccentric geosynchronous transfer orbit (GTO) having an apogee radius near 85,000 kilometers and an inclination of 28.5 degrees. Using a restartable Liquid Apogee Motor (LAM), the orbit will be placed using approximately 6 orbit maneuvers into a geosynchronous equatorial orbit with an inclination below 0.5 degrees. While maneuvering toward geosynchronous orbit, the spacecraft will also be phased in longitude by specific timing of these burns. The GOES Program places its operational satellites at the longitude locations of 75.0 degrees and 135.0 degrees West longitude. If fully functional satellites are already in place at those locations, GOES-N may be kept in a storage condition near 105.0 degrees West longitude.

Flight Dynamics personnel play a critical role in placing the spacecraft at its desired location during geosynchronous L&EO operations. A carefully constructed L&EO flight operations script depends heavily on the timing of events and products that are computed by Flight Dynamics personnel. Although the role of the GSFC Flight Dynamics Team is different from that of past missions, we are still ready to provide our best efforts and experience to make GOES-N a success.

[Technical contacts: R. DeFazio]

2.2.6 Landsat-5: End of Life?

Not so fast! It is true Landsat-5 suffered a loss of its primary imaging mode, but the mission is far from over. Near the end of 2000, the Landsat-5 instrument shutter began to lose synchronization with its scan mirror so that the shutter would periodically obscure the Earth over part of the image area, resulting in what has come to be known as "caterpillar tracks" in some of the images. At first, the instrument was used sparingly to save it for specific images, but eventually the effect came to manifest itself in more and more of the images. This eventually forced consideration of either a more effective means

of dealing with the problem or declaring the mission over and commencing de-orbit procedures on what was an otherwise healthy spacecraft. Since we aided USGS (who currently runs Landsat-5) in the de-orbit of its sister spacecraft, Landsat-4, Code 572 was asked to be present at several discussions regarding the option of de-orbiting Landsat-5.

Meanwhile, Flight Operation engineers devised a brilliant scheme to continue the mission by controlling the scan time to a nominal value that is within the control envelope of the calibration shutter rather than the nominal Scan Angle Monitor (SAM) mode, in which the calibration shutter passes in front of the scan mirror during the mirror's non-imaging period. This so called "Bumper Mode" comes at the price of losing the precision knowledge of the mirror position (as would normally be reported in the SAM mode) but this deficiency can be accommodated on the ground; as a result, Landsat-5 may be expected to provide useful data for years to come. The fix to this problem has permitted Landsat-5 the continued ability to outlast its designed mission life—launch was in March of 1984, and the mission was to be five years long—and has long term implications for Landsat-7, whose Enhanced Thematic Mapper can be expected to suffer the same problem as it ages.

Code 572 is charged with creating and maintaining contingency de-orbiting plans, which would be engaged should the spacecraft mission ever be declared over for any reason. Since that now appears to be pushed off until further notice, we have run a long-term reentry analysis assuming an end-of-life declaration every year for the next five years and remain ready to respond should we get the call.

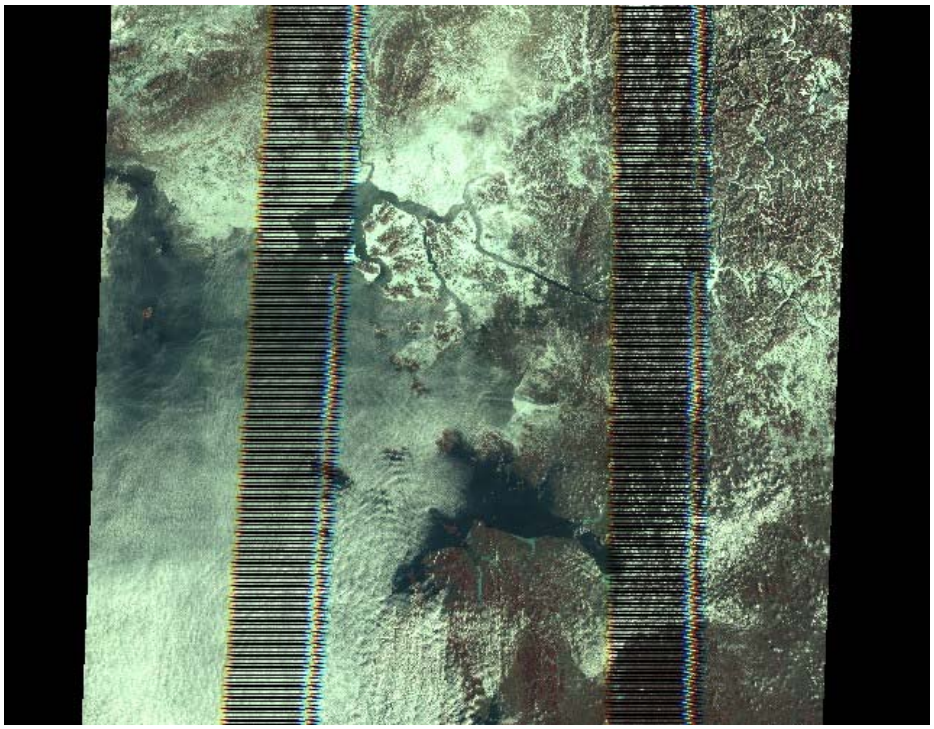

Figure 2-12. Landsat-5 Image With "Caterpillar Tracks" Present

[Technical contacts: David Quinn, Bob DeFazio]

2.2.7 Meteor/SAGE

The SAGE III/Meteor-3M satellite mission is a joint partnership between NASA and the Russian Aviation and Space Agency (RASA). It was initiated by the Gore-Chernomyrdin Commission in 1994 and extends a long-term working relationship between the United States and Russia to understand Earth's environment.
SAGE III was successfully launched onboard a Meteor-3M spacecraft on December 10, 2001 at 17:18:57 UTC from the Baikonur Cosmodrome in Kazakhstan. The satellite is in a sun-synchronous orbit with an ascending node time of about 9 AM.

The primary navigation system for SAGE III was a GPS/GLONASS receiver. Shortly after launch, it was determined that problems with the receiver could not be rectified and an alternative navigation source was needed. FDAB met with project personnel to discuss alternatives. It was decided to use ground laser ranging for orbital tracking since no two-way transponder was onboard the spacecraft. Code 926 was asked to provide orbit determination based upon the laser ranging data. SAGE III has continued with its successful mission.

[Technical contact: Mark Beckman]

2.2.8 Microwave Anisotropy Probe (MAP)
http://map.gsfc.nasa.gov

FY 2002 has been another productive and busy year for the MAP team. MAP was successfully launched on June 30, 2001 at 19:46:46 Z from the Eastern Range at Cape Canaveral, FL, aboard a Delta II 7425 expendable launch vehicle. MAP is currently at its mission orbit, a Lissajous orbit about the L_2 Sun-Earth Lagrange point, which is about 1.5 million km from Earth in the anti-Sun direction. This location and orbit were selected to minimize environmental disturbances and maximize observing efficiency. At L_2, the spacecraft is being maintained such that the MAP-Earth vector remains between 0.5° and 10.5° off the Sun-Earth vector to satisfy communications requirements while avoiding eclipses. The MAP mission lifetime is 2 years with a goal of 4 years, which will make MAP the first spacecraft to orbit about the L_2 Lagrange point for up to 2 years. The MAP satellite arrived at L_2 on January 2, 2002. The maneuver team has successfully completed a number of important milestones during this year.

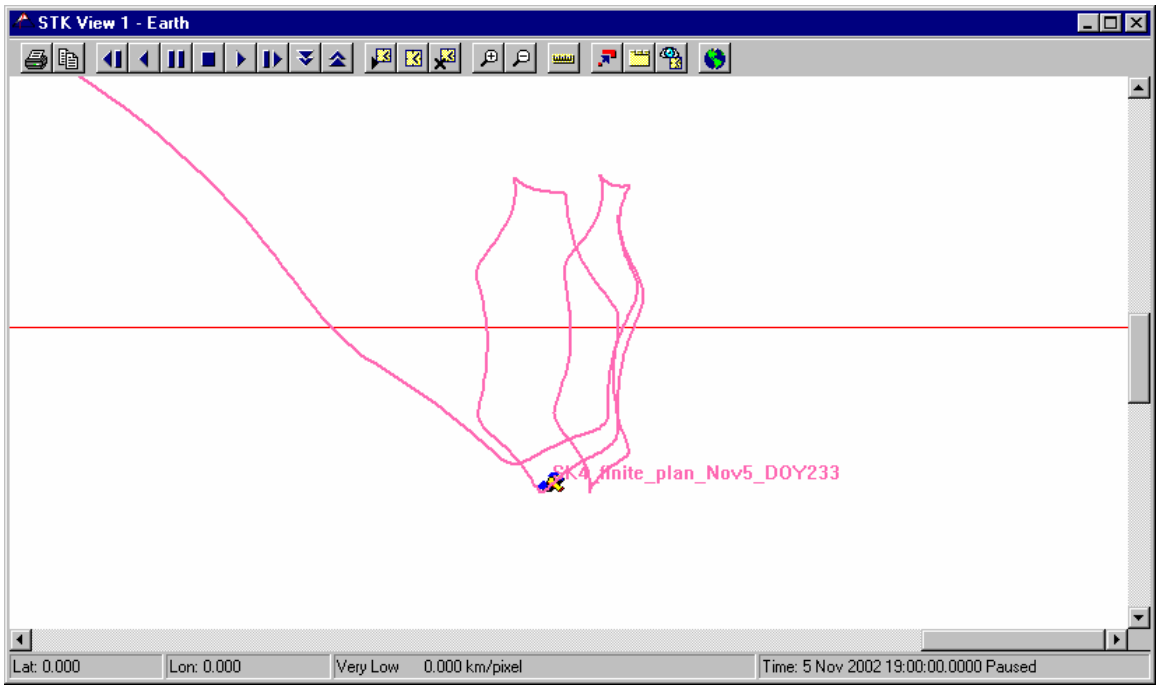

Figure 2-13. Trajectory From SK3 Balanced With SK4 Performed on November 5, 2002

MAP support during FY02 has mainly consisted of planning and supporting maneuvers to keep MAP in its nominal Lissajous orbit. To date, there have been three such stationkeeping maneuvers (named SK1, SK2, and SK3). The trajectory from SK3, balanced with an SK4 performed on November 5, 2002, can be seen in Figure 2-13. For each of the maneuvers the trajectory team was responsible for planning each maneuver and determining what would happen in the case of certain contingencies. The planning process involves several critical steps. First, the team determines the direction and magnitude of the burn. This is accomplished by targeting a maneuver at least three months downstream that will meet the requirements of being less than 1 meter per second. Once the magnitude of the maneuver is determined, the trajectory team calculates the desired attitude for that maneuver. The spacecraft attitude must meet several criteria during the burn. First, it must place the spacecraft z-axis 19 degrees off the Sun line, balancing thermal, power and attitude control concerns. Second, during the maneuver, the spacecraft z-axis must move away from the Sun line (the motion is due to the torque on the spacecraft caused by the canting of thrusters 1 & 2). Third, the attitude is chosen such that the delta-V direction lies as close to the velocity vector as possible. This third constraint allows for the most efficient maneuver given the other two constraints. Once the attitude is determined, the finite maneuver is planned.

For the SK3 maneuver, a new procedure was added that allows the maneuver planning team to more accurately match what the HiFi and FlatSat simulators predict for the burn, which improves the accuracy of the burn. This additional iteration consists of generating

a maneuver plan using predicted thruster duty cycles that are typical of stationkeeping maneuvers. The maneuver support has been extremely successful. All three maneuvers have been well within requirements (see table below). The next maneuver (SK4) is scheduled for November 4, 2002. The trajectory team has also refined and updated the stationkeeping maneuver procedures and has recently started training the spacecraft controllers so that they can support future stationkeeping maneuvers.

	Delta-V (cm/s)		Duration (sec)		Mass Loss (kg)		Scale Factor	
Maneuver	Pred	Actual	Pred	Actual	Pred	Actual	Pred	Actual
SK1	42.94	43.50	73.20	72.92	0.186	0.188	0.935	0.950
SK2	34.80	35.06	54.08	53.84	0.162	0.159	0.970	0.982
SK3	45.96	46.60	72.48	71.84	0.213	0.211	0.970	0.983

Table 2-1. Planned versus actual results for the three stationkeeping burns.

In addition to the maneuvers described above, there was a Safehold incident at about 10 pm EST on November 5, 2001. A “Hardware-Cold” reset had occurred, which originated in the Power On Reset (POR) circuit of the Mongoose V processor card, and was caused by a single event transient (SET) due to heavy ions from a very intense solar storm that occurred November 5 & 6, 2001. This condition was discovered at the onset of MAP's ground pass at 9 am Nov. 6. Both sets of attitude control electronics (ACE) were in correct configuration, with the ACE Safe-Hold controlling to within 1 degree of the Sun line. The particular configuration indicated the reason for Safe-Hold was some reset of the Mongoose processor, rather than a failure of any ACS component.

Fortunately, there was no evidence of permanent damage to any components, and we were able to exit Safehold by 12:45 pm and reconfigure back to Observing Mode by 1:40 pm. We watched MAP for a full precession period (one hour) and then declared a return to nominal operations and terminated our Spacecraft Emergency status. The whole MAP Team responded quickly and efficiently to the anomaly, and rapidly and safely returned the MAP Observatory to Observing Mode. The Flight Software, ACS, Command Control & Communications, Systems Engineering and Spacecraft Mission Operations Center control teams, and the Code 561 Radiation Group were instrumental in the investigation of this anomaly. MAP has operated without incident since this event.

System momentum buildup on-orbit has been less than 0.01 newton-meter-seconds (Nms) per day. This means that MAP can easily go three or four months between stationkeeping burns with its system momentum remaining below the 3-Nms performance limit. The maximum system momentum on orbit was 1.45 Nms, seen just before the first stationkeeping maneuver, as shown in Figure 2-14.

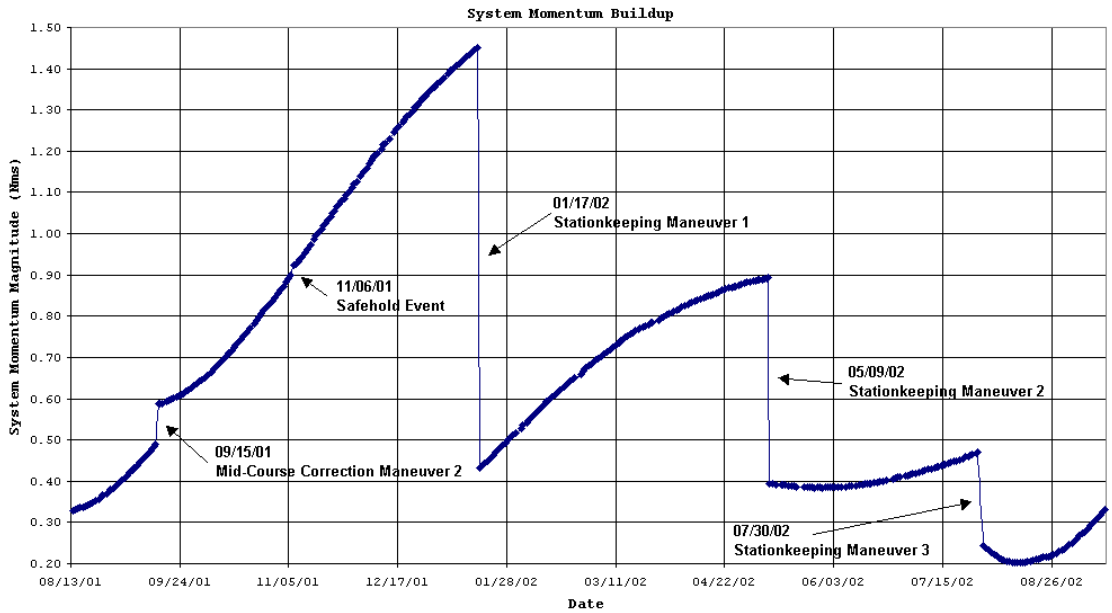

Figure 2-14. MAP System Momentum History

The MAP GNCD support team wrote a significant numbers of papers during this fiscal year, and was presented with two team awards. The list of papers and awards may be found in the Appendix of this document.

[Technical contacts: Osvaldo O. Cuevas, Stephen Andrews]

2.2.9 Rossi X-ray Timing Explorer (RXTE)

http://guinan.gsfc.nasa.gov/docs/xte/xte_1st.html

Since 1995, the RXTE has been observing bursts of X-rays that come from high-energy phenomena including black holes, neutron stars, and X-ray pulsars. The RXTE performs multiple slew maneuvers, to point to the various ground selected targets. RXTE can dwell on a target with arcsecond pointing accuracy. This tight pointing can be accomplished using high-precision gyros and star trackers. The star tracker updates any type of drift that the gyros might produce by using a Kalman filter.

On November 25, 2001, the RXTE star tracker failed to establish lock onto a particular set of stars. One of the stars had a variable, near-neighbor star that was not in the onboard catalog. At that time, the near neighbor star was bright enough to pull the spacecraft off its known attitude. As RXTE slewed to new targets, the star tracker algorithms were unable to get an attitude fix and, therefore, did not correct for any gyro drift. To recover, the Flight Operations Team (FOT) sent a set of commands that had previously been developed by the FDAB and the FOT. The FOT also attempted to use the Real Time Attitude Determination System (RTADS) that was developed by the FDAB. Neither method worked, so the FOT contact the FDAB for support.

Figure 2-15. Rossi X-ray Timing Explorer (RXTE)

The FDAB was able to determine that the commands were initially sent while the Earth occulted the star tracker field of view. It was also determined that the RTADS in the FOT had been set to a wrong configuration. After the FDAB reconfigured the RTADS and worked with the FOT to determine the proper orbit geometry, the RTXE was successfully reset to its proper attitude.

The lessons learned covered three areas. First, it was made clear to the FOT that attitude knowledge loss is not part of normal operations. The urgency within the control room should be heightened. Second, a launch-style checklist was developed. This will verify all ground systems and spacecraft configurations before the recovery commands are sent. Third, recovery procedures must be rehearsed with the oversight of an independent test conductor.

[Technical contact: Dave Mangus]

2.2.10 TDRS-I Support

http://tdrs.gsfc.nasa.gov/tdrsproject/

Several months before the launch of TDRS-I, concerns were raised about the satellite's Hemispherical Resonator Gyro (HRG). HRGs ingest helium, and if contaminated with too much they can take a significant amount of time to start up. Because the TDRS-I HRGs were going to be powered off and then back on soon after launch—to switch from the high-rate mode needed at launch to the more accurate low-rate mode used for the rest of its operations—the concern was for the health of the spacecraft if the HRGs failed to restart in the nominal amount of time. The TDRS-I contractor addressed these concerns

by running a dry nitrogen purge to slow the degradation of the HRGs before launch, and by identifying a power- and thermal-safe, spin-stabilized orientation that the spacecraft could adopt if the HRGs did not start up correctly. Flight Dynamics Analysis Branch analysts Jim O'Donnell and Steve Andrews were asked to verify that this orientation would keep TDRS-I safe without gyros during its geosynchronous transfer orbit (GTO).

By collecting information on its mass properties and the planned spin-stabilized gyroless control mode, the FDAB analysts were able to quickly put together a simulation of TDRS-I in its GTO orbit. Using this simulation, the analysts verified that the gyroless control mode would allow the spacecraft to remain power-safe through a number of orbits, well past the worst-case HRG restart time.

TDRS-I launched on March 8, 2002, at 5:59pm, and there were no problems with the restart of its HRGs. The spacecraft did suffer an on-orbit anomaly after launch related to its propulsion system. At the time of this writing, work continues to be done to try to get TDRS-I as close as possible to its planned geostationary orbit.

[Technical contact: James O'Donnell]

2.2.11 Tropical Rainfall Mapping Mission (TRMM)

http://trmm.gsfc.nasa.gov/
http://trmm-fot.gsfc.nasa.gov/

TRMM has executed 69 Delta V maneuvers since a boost to a 402 km altitude orbit in August 2001. In addition, 14 yaw maneuvers have been performed in the past year. During the orbit boost, the Earth Sensor Assembly performance degraded to the point that it could no longer be used to control the spacecraft attitude. The Kalman filter was enabled during the boost phase, and has been running continuously since then.

It was found that the Precipitation Radar (PR) data from TRMM could be used to measure the roll attitude error, and this data showed that TRMM was not meeting pointing requirements after the Kalman filter was turned on. There were several improvements made to the flight software and the ground system data processing that greatly improved the accuracy of the Kalman filter. Some of the changes were to onboard software, and other changes were to the ephemeris processing; a detailed description of the changes made may be found in the following reference:

S. Andrews, S. Bilanow, "*Recent Flight Results Of The Trmm Kalman Filter*",AIAA-2002-5047, AIAA GNC Conference, Monterey, CA, August 5-8, 2002.

The result of the changes is that the attitude error, as determined by the PR data, is now less than 0.2 degrees, peak-to-peak, as shown in Figure 2-16. The ephemeris errors also have been substantially reduced, as indicated in Figure 2-17.

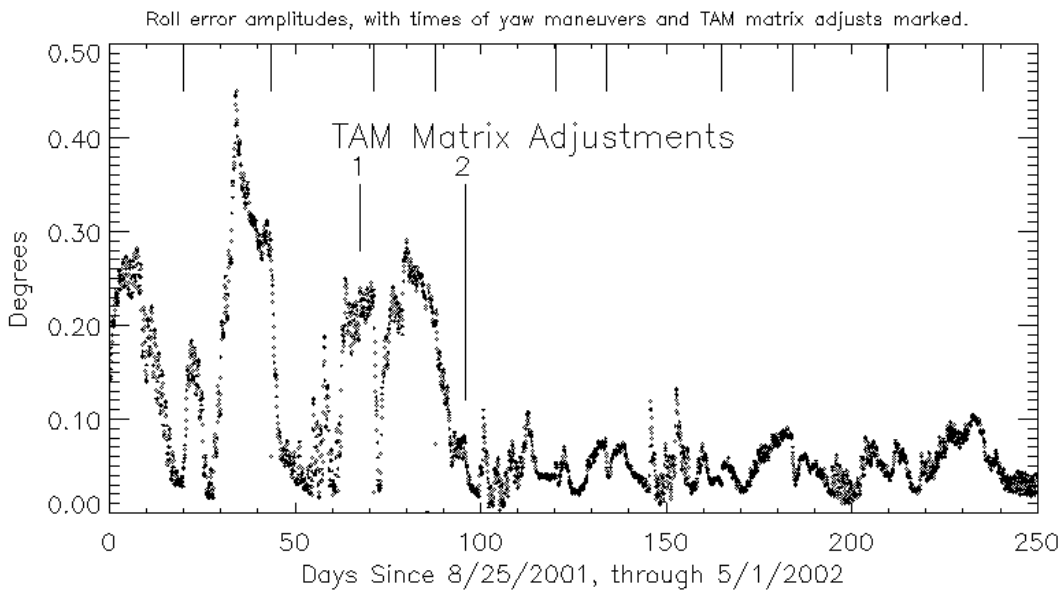

Figure 2-16. TRMM Attitude Error

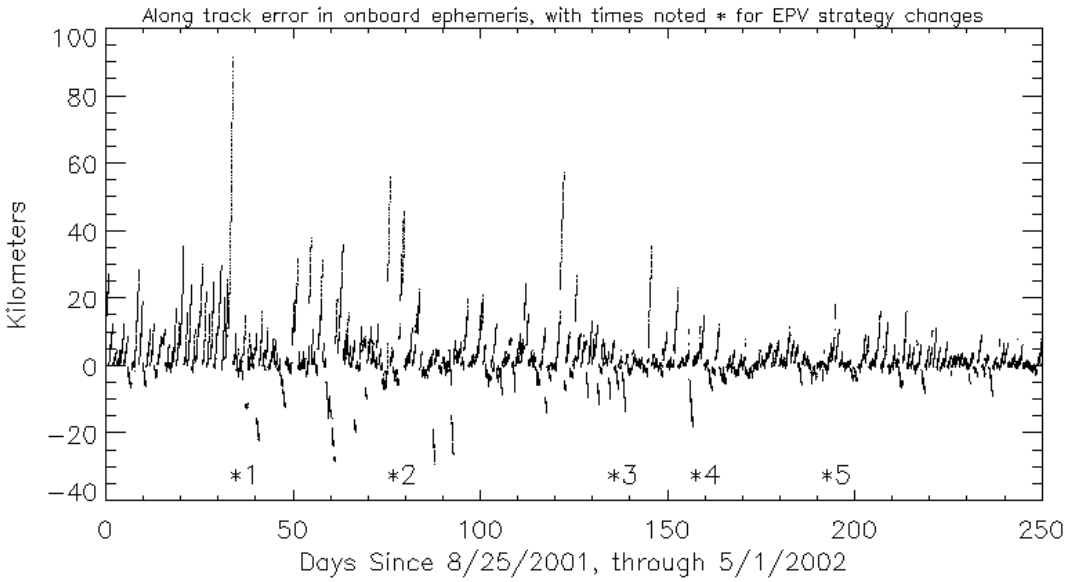

Figure 2-17. TRMM Ephemeris Error

Reentry planning got underway in earnest on TRMM this year. A TRMM Reentry GN&C Peer Review was held on June 11, 2002. Brent Robertson (GNCD System Engineering Branch Head) had been coordinating and leading this effort.

Re-entry Maneuver Planning (F. Vaughn)

A baseline maneuver sequence to de-orbit TRMM was developed. Analysis was performed to characterize the impact footprint based on variations in thruster performance and ballistic coefficient. The impact of partial or missed maneuvers on the maneuver sequence was assessed to develop contingency procedures.

ACS Analysis / Simulations (J. Morrissey)
Attitude control system analysis for the TRMM re-entry has been performed using the existing TRMM HiFi Simulator. Simulation runs are performed for every aspect of the TRMM re-entry to verify desired pointing and system stability. The simulator is also used to predict fuel usage for the ACS that goes into the overall fuel budget for the re-entry operation. A high fidelity aerodynamic model has been added to the simulator in order to increase the accuracy of performance predictions at low altitudes where higher atmospheric density will produce large torques on the spacecraft during re-entry. Prior to the final burn that will re-enter TRMM the spacecraft must survive a low perigee pass (150 km altitude) in the presence of these high aerodynamic torques. It was found using the TRMM HiFi Simulator that the reaction wheels could not store enough angular momentum to maintain nadir pointing through this perigee pass. This problem was solved by modifying the thruster-based momentum unloading mode to perform as a PD controller that maintains nadir pointing. The modifications were added to and verified on the TRMM HiFi Simulator. A software patch that implements this modification will be uploaded to the spacecraft before re-entry operations.

Reentry Operations Timeline (S. Andrews)
A timeline and Absolute Time Sequence (ATS) structure was developed to perform the controlled re-entry. The existing ATS and timeline for stationkeeping maneuvers were modified to allow the spacecraft to perform the following functions:

Delta H mode test
Burn #1
Burn #2
Perigee Delta H attitude hold
Burn #3

A more formal timeline and complete ATSs will be developed next.

FDC Configurations (D. Mangus)
Due to the criticality of the reentry maneuvers, the nominal Failure Detection and Correction (FDC) configuration is not adequate for this phase of the mission. The maneuvers have to go as planned, so failures or anomalies that do not directly affect the maneuvers must not be allowed to abort the burns. Detection limits and thresholds have been examined, as well as actions by the spacecraft and ground. The goal is a configuration that minimizes risk to the maneuvers and the spacecraft, while at the same time maximizes the chance of a successful controlled reentry.

Risk Analysis (D. Mangus)
In the course of the FDC analysis, a risk management approach was started. The idea is to look at risks to successful completion of the reentry, and to try to quantify the

probability and criticality of those risks. Then the effort is put into managing the high probability or high criticality risks. Some of the risks identified are component failures, inadequate performance, aborted maneuver, and the spacecraft reconfigurations necessary to perform the reentry.

Aron Cooper, a co-op student, was available during the summer of 2002 to do some work on TRMM. He was tasked with using flight data from the orbit maintenance maneuvers in combination with equations of motion to try to estimate how much fuel was remaining on the spacecraft. The goal to help verify the propulsion and flight ops teams' fuel estimates, since this is critical to determining when reentry will start. Unfortunately, Aron found that the fuel mass estimate was extremely sensitive to other spacecraft parameters (such as thruster force for the maneuver), and a satisfactory fuel mass was not found.

The –Y solar array drive assembly (SADA) seized during a large array slew on September 4, 2002. This occurred after a long period of array inaction due to solar array feathering (initiated to try to increase mission life by reducing the effects or aerodynamic drag). The SADA eventually started moving again during the slew period, but the deployables subsystem engineer felt it best to fix the array at a 0° rotation angle (feathered with respect to velocity) to prevent a lock up at some other position. This has led to a lot of analysis and simulation to show that the ACS and power systems can operate with one array fixed and one array feathered, both for nominal mission activities, and for the controlled reentry. Code 572 engineers have been instrumental in simulating the proposed configuration, and determining the software changes required to do the change. A peer review was held September 19, 2002, and a plan was put in place to fix the –Y array, and to fully operate the +Y array. This work will be the focus of the TRMM engineers for the next few months.

[Technical contacts: Stephen Andrews, Jim Morrissey, Frank Vaughn, Dave Mangus]

2.2.12 Mission Services Program Office (MSPO)

The FDAB supported the MSPO by providing consultative support for the initial planning of the move of the Flight Dynamics Facility (FDF). The move of the FDF will consolidate all of the operations facilities that the MSPO oversees and provide for more efficient system and facility security. In its consulting capacity, the FDAB assisted the MSPO in reviewing the high level plan for the move, provided input for the new facility modifications and layout and reviewed schedule and budget. Since the move to the new facility is expected to take about 12 months, the FDAB will be continue to provide consulting support to MSPO for the planning, contract monitoring and equipment procurement related to the move for fiscal year 2003. The FDAB will also assist in the implementation of the FDF move plan.

[Technical contact: Sue Hoge]

3.0 Study Mission Support

3.1 Constellation X

Constellation X is a study mission that uses 2 (possibly 4) x-ray telescopes in constellation at the Earth's L2 libration point to study black holes and galaxy formation. The instrument consists of a large area X-ray mirror with 100-meter focal length. The baseline plan is to launch the spacecraft in pairs aboard an Atlas V launch vehicle.

This year the FDAB has provided support to the Constellation X study team in the area of trajectory design. The baseline trajectory is an orbit about the Sun-Earth L2 libration point. FDAB provided input to the baseline Reference Mission Description document, which is being rewritten for release next year. The input included a delta-V budget, input on possible orbit determination systems that could be flown onboard, and evaluation of the orbit determination requirements. The team also participated in discussions regarding the mission timeline and separation mechanism from the launch vehicle. In addition, analysis of cross-link navigation capabilities that could be used to support Constellation X are ongoing as a branch technology effort. For additional information on that effort, please see the Celestial Navigation topic in the Autonomous Navigation Technology section of this report (section 4.2.2).

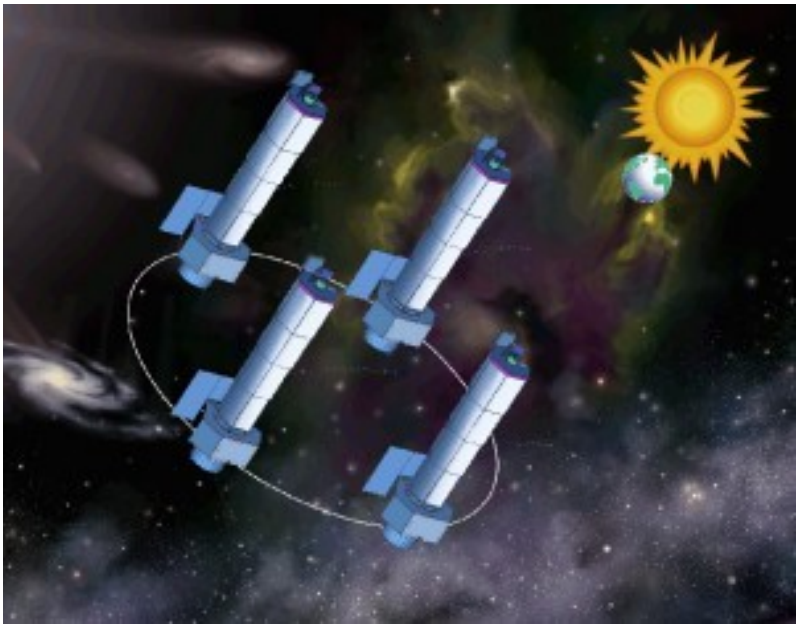

Figure 3-1. Constellation X

[Technical contact: Lauri Newman]

3.2 Geospace Electrodynamic Connections (GEC)

The Geospace Electrodynamic Connections (GEC) mission is a multi-spacecraft mission managed out of NASA's Solar Terrestrial Probe (STP) office at the Goddard Space Flight Center, Code 460. Currently in the formulation phase, GEC plans to use four spacecraft to study the Earth's Ionosphere-Thermosphere (IT) system. While this region has been studied before, the coordinated use of four spacecraft will allow the scientists to:

1. discover the spatial and temporal scales on which magnetospheric energy input to the IT region occurs
2. determine the spatial and temporal scales for the response of the IT system to this input of energy
3. quantify the altitude dependence of the response

The four GEC spacecraft will be launched on a Delta-II 2920 expendable launch vehicle into a 185 km x 2000 km, 83° orbit no earlier than September, 2009. After separation from the launch vehicle, the GEC spacecraft will initialize a "pearls on a string" formation with uneven inter-satellite spacing that will be varied during the course of the mission. . The uneven spacing of the four spacecraft will allow GEC to be able to resolve six different temporal and spatial scales. The spacing will vary from a goal of 10's of seconds up to a quarter orbit throughout the life of the mission. GEC also plans to perform periodic "deep dipping" campaigns where all four spacecraft will lower their perigee to an altitude near 130 km. Excursions to this altitude were performed by Atmospheric Explorer C (AE-C) in 1975, but the multi-satellite nature of GEC will collect more data while also carrying instruments that AE-C didn't (eg, electric field booms).

Figure 3-2. GEC Spacecraft Formation

During FY02, Flight Dynamics supported an industry study of GEC conducted through the Rapid Spacecraft Development Office (RSDO). After an open competition of RSDO vendors, two spacecraft contractors were selected and received funding for a 100-day study of the GEC concept. FDAB engineers supported the studies through consultation of the GEC mission during the study period and by providing technical reviews at the mid-term and end-term presentations.

FDAB work is continuing in the areas of the GEC operations concept. This includes investigations of the initial spacecraft formation after launch vehicle separation and how to initiate and terminate the dipping campaigns for the entire four-spacecraft formation. Further work will examine the possibility of establishing a form of a repeat cycle for GEC to enhance the science data return.

[Technical Contact: Michael Mesarch]

3.3 James Webb Space Telescope (JWST)

On September 10, 2002, NASA selected TRW, Redondo Beach, Calif., to build the Next Generation Space Telescope (NGST). In addition, the space-based observatory will be known as the James Webb Space Telescope, named after James E. Webb, NASA's second administrator.

The James Webb Space Telescope is scheduled for launch in 2012 aboard an expendable launch vehicle. It will take about three months for the spacecraft to reach its destination, an orbit 940,000 miles or 1.5 million kilometers in space, called the second Lagrange Point or L2, where the spacecraft is balanced between the gravity of the Sun and the Earth. See Figure 3-3 below for nominal trajectory.

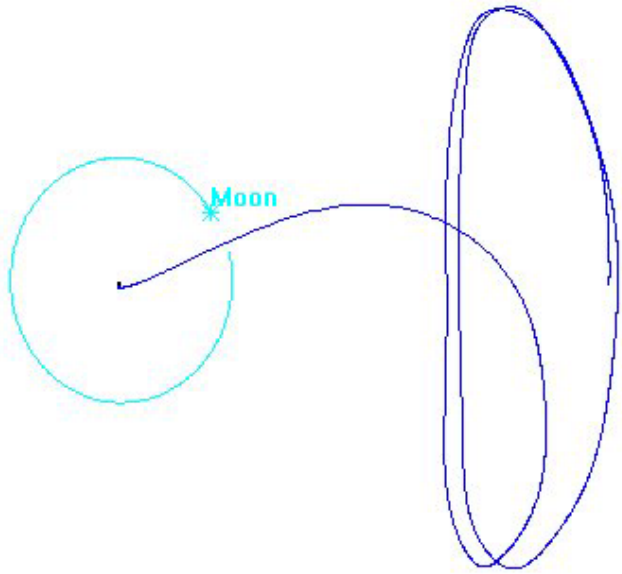

Figure 3-3. JWST L2 Trajectory

FDAB has been chosen by TRW to provide flight dynamics support of JWST. This support begins with a kick-off meeting at TRW the week of November 18, 2002. FDAB will provide trajectory design, mission planning, and orbit determination support for JWST.

FDAB also participated in a significant investigation into the design of JWST at the request of NASA HQ. FDAB was asked to investigate scenarios that include launch from the U.S. Space Shuttle and the possible servicing of JWST. FDAB came up with several different options for launch from STS including:

- Use of a bi-prop engine with 8+ perigee burns to reach L2
- Use of different ion engine configurations to reach L2 via low thrust

FDAB also determined several scenarios in which JWST could be serviced including:

- Launch of an separate ion tug to bring JWST back from L2 to LEO which would include the first ever spacecraft rendezvous in LPO
- Use of the bi-prop engine to bring JWST back to Earth with the use of aerobraking to capture into LEO

The baseline mission remains the TRW proposal of an ELV launch with no serving option however.

[Technical contacts: Mark Beckman, Dave Folta]

3.4 Leonardo

http://climate.gsfc.nasa.gov/~wiscombe/LeoBRDF/LeoBRDFhome.html

The purpose of the Leonardo mission is to define the Bi-directional Reflectance Distribution Function (BRDF) of sunlight off of Earth's clouds. According to Warren Wiscombe, the Leonardo Principal Investigator (PI),

> "…one of the most important [uses of the BRDF] is to reduce the currently large errors in estimates of radiative forcing due to air pollution, dust outbreaks, biomass burning fires, hurricanes, and other natural and anthropogenic phenomena. Radiative forcing is the *lingua franca* of global change in general, and of global warming in particular. It provides the common measurement scale by which phenomena as disparate as CO_2 increase, cloudiness changes, and desertification can be compared."

Leonardo consists of a constellation of spacecraft that simultaneously measure the sunlight reflectance off of a cloud from different perspectives. Analysis over the past year focused on a constellation of six spacecraft in near-equatorial low Earth orbits. The spacecraft look at clouds that are above the equator and centrally located with respect to the constellation. Constellation maintenance occurs once per month to account for orbit perturbations and the Sun's position. A genetic search algorithm was used to find optimum constellation formations for each month. Optimality was based directly on the

PI's science algorithm. Future work includes calculating minimum propellant transfers from one formation to the next, as well as determining the propellant required for constellation initialization.

[Technical contact: Alexander Barnes, Steve Hughes]

3.5 Laser Interferometer Space Antenna (LISA)

The primary objective of the Laser Interferometer Space Antenna (LISA) mission is to detect and measure gravitational waves from massive black holes and galactic binaries in the frequency range between 10^{-4} and 0.1 Hz. The LISA mission comprises three identical spacecraft, 500,000 km apart, which form an equilateral triangle (Figure 3-4). The center of the spacecraft formation is in the ecliptic plane, 1 AU from the Sun and 20° behind the Earth. LISA can essentially be viewed as a Michelson interferometer in space, with a third arm to provide wave polarization information as well as redundancy. Each spacecraft contains two optical assemblies, with each assembly pointing toward an identical assembly on each of the other two spacecraft (figure 1). A 1-W infrared laser beam (1 μm wavelength) is transmitted to the remote spacecraft via a telescope. The incoming beam is focused on a sensitive photodetector where it is superimposed with a fraction of the original local light. Each optical assembly includes an enclosure containing a free-flying proof mass, which serves as an optical reference mirror for the light beams. A passing gravitational wave changes the length of the optical path between the proof masses in one arm relative to the other arm. The spacecraft is used to provide a drag-free environment for each of the proof masses within it by shielding the masses from solar radiation pressure. In order to be able to detect gravitational strain levels to the order of 10^{-23}, tight pointing and positioning requirements are placed on the spacecraft and the proof masses (e.g., acceleration requirement on each proof mass: $3\text{x}10^{-15}$ $m/s^2/Hz^{-1/2}$). To achieve these requirements, the LISA spacecraft are baselined to use electric propulsion thrusters and quadrant photodiodes for position and attitude control of each spacecraft, and capacitive sensing and actuation for relative positioning of each proof mass to the spacecraft.

The FDAB personnel supported the LISA mission in a couple of areas: (1) Dynamics and control modeling and analysis; and (2) Design and analysis of Disturbance Reduction System (DRS) control. Each of theses contributions is described in the following paragraphs.

A 19-degrees-of-freedom (DOF) model of a LISA spacecraft was developed. This model captures the complete rigid-body dynamics of a typical LISA spacecraft in formation with two others. Dynamically, it includes all rigid-body degrees of freedom, six for the S/C translation and rotation; six for each proof mass translation and rotation; and, finally, one rotational DOF for telescope articulation. A number of disturbance sources, both internal and external, are included. Measurement noise for quad detector and capacitive sensing, as well as actuation noise models for the Micro-Newton Thrusters and electrostatic suspension controls are included. Orbital dynamics are brought in via the

ephemeris file, which was obtained using orbit optimization. For the purpose of this model, the direction of the incoming beam is simulated with the aid of the orbital ephemeris data file for LISA, where the nominal orbital positions of the three LISA spacecraft are provided. Nonlinear electrostatic forces and torques, as well as those from self-gravity, are modeled via a linear time-invariant system. Moreover, electrostatic actuation and sensing cross-talks are also modeled. The five control systems that comprise the LISA Disturbance Reduction System (DRS) are included in the model. These are the attitude control system (ACS), to maintain the pointing of the two telescopes with respect to two incoming beams from the other spacecraft; the drag-free control (DFC), which commands the positioning of the spacecraft to center about the proof masses (PM); the proof mass suspension control, to maintain the position and attitude of the proof mass with respect to its caging; and the telescope articulation loop, to maintain the optical link between the spacecraft as the angle between the spacecraft varies according to the natural propagation of the orbits of the spacecraft.

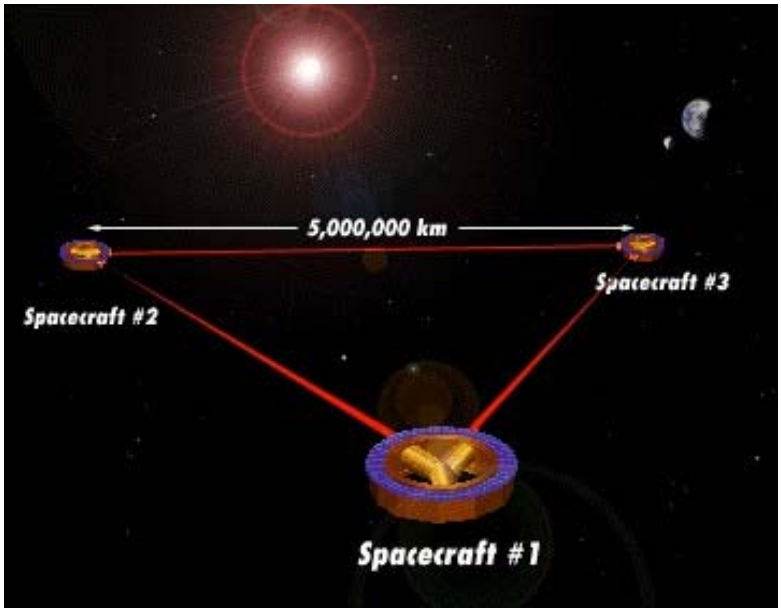

Figure 3-4. Laser Interferometer Space Antenna (LISA)

DRS control is a critical part of the LISA mission. It includes the overall control system architecture for the positioning and pointing of the spacecraft as well as the proof masses relative to the spacecraft. In the baseline configuration, the spacecraft is responsible for maintaining a total drag-free environment in the sensitive axes for each of the proof masses. At the same time, fine pointing of each spacecraft with respect to the other two has to be maintained continuously. Preliminary design work for DRS control to achieve the desired pointing and positioning accuracy has been completed. Digital control loops have been designed for each of the five control systems. Two designs have been considered for the drag-free loop. In the first design, a centralized approach is followed wherein the S/C position and the proof mass translation commands are computed in a centralized manner to achieve drag free motion of the test masses. In the second design, however, the spacecraft is positioned to maintain drag-free motion in the sensitive axes,

while the proof mass suspension control ensures that the masses follow their respective housings in the transverse directions. The attitude control loop uses the measurements from the two quad detectors, and computes appropriate S/C attitude error and telescope articulation commands to ensure that the optical links between the spacecraft are maintained to the desired accuracy.

[Technical Contact: Peiman Maghami]

3.6 Lunar Science Explorer

The Lunar Science Explorer (LSE) principle investigators visited the Integrated Mission Design Center (IMDC) the week of March 4, 2002 and again the week of April 2. The LSE is a Discovery class mission designed to obtain a detailed topography map of the moon. The mission will map the surface of the Moon over 2 years using laser altimeters. The mission orbit was chosen to be circular, with a 30 km mean altitude above the Lunar surface. This altitude was chosen to maximize science while minimizing the fuel budget, or dV cost, of orbit maintenance (14 m/sec per month). The direct transfer option was chosen after a comparison with Weak Stability Boundary (WSB) and low-thrust options. The direct transfer takes 4.7 days and requires 3 dV maneuvers to capture and lower the altitude about the Moon (see Figure 3-5). No significant savings could be identified with the WSB, and the low-thrust option was too power-intensive. The total mission dV will be 1460 m/sec.

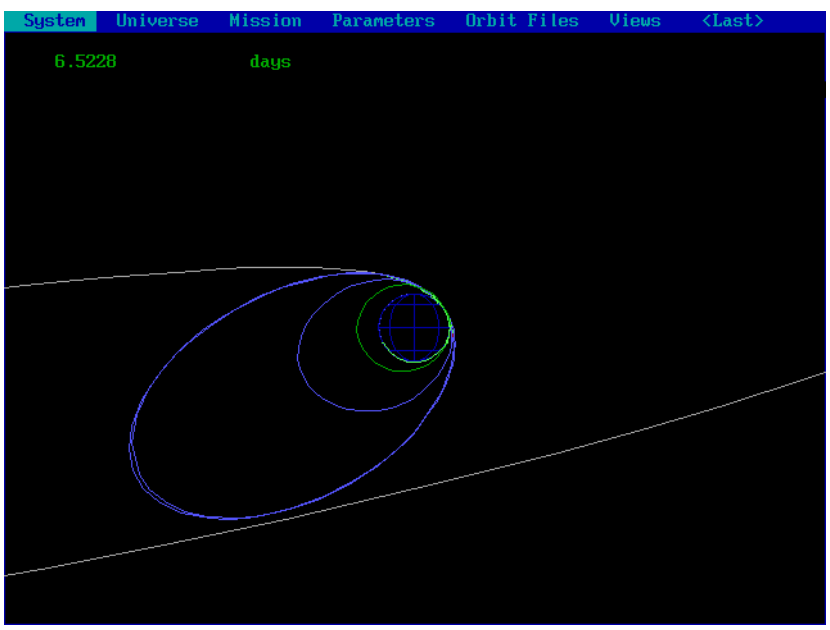

Figure 3-5. LSE Lunar Capture

Orbit determination for LSE will be quite challenging. In order to provide the science quality requested, orbit determination accuracy to 1 meter (radial) is necessary. However,

at 30 km altitude, the uncertainty in the lunar potential model gives a radial uncertainty of 28 m (as determined by Lunar Prospector orbit determination results). The only way to meet the OD requirements is to use LSE Doppler data to generate an updated lunar gravity model specific to the 30 km polar orbit. Mars Global Surveyor OD accuracy improved three-fold, from beginning of mission to end, due to gravity model tailoring.

[Technical contact: Mark Beckman, David Folta]

3.7 Magnetospheric Multiscale Mission (MMS)

http://stp.gsfc.nasa.gov/missions/mms/mms.htm

MMS is part of the Sun-Earth Connection program, one of the four principal science themes of NASA's Office of Space Sciences. The major focus of the Sun-Earth Connection program is investigating the physical processes that link the Sun and the Earth. MMS is a four-spacecraft solar-terrestrial probe designed to study magnetic reconnection, charged particle acceleration, and turbulence in the key boundary regions of the Earth's magnetosphere. An Announcement of Opportunity for the instrument complement and principle investigator teams is scheduled for September, 2002, selection of multiple payload science teams in early 2003, and final selection of one team about a year later.
The mission consists of four science phases. The main result of the past year's effort has been to determine the general characteristics of the trajectories for these phases. Phase 3 involves two lunar flybys to set up the trajectories for phase 4. The analysis effort is not complete, but much about the orbit dynamics for these phases has been learned and added to what we already knew about phases 1 and 2. After the Principal Investigator teams have been selected, the analysis for all four phases can become more specific.

A paper, "The Double Lunar Swingby of the MMS Mission," authored by personnel from a.i. solutions, Inc, was presented in December 2001 at the16th International Symposium on Space Flight Dynamics in Pasadena, California. The complete paper is available at http://issfd.jpl.nasa.gov/sessions/10session/64_Edery.pdf.

Two more papers are in preparation for a conference in early 2003.

[Technical contact: Charles Petruzzo]

3.8 Themis

Themis was one of four MIDEX missions selected on April 17, 2002 for Phase A studies. Down selection to two will occur by March 2003. If selected, THEMIS will be launched in the spring/summer of 2006.

THEMIS's five identical probes measure particles and fields on orbits which optimize tail-aligned conjunctions over North America. Ground observatories time auroral breakup

onset. Three inner probes at ~10Re monitor current disruption onset, while two outer probes, at 20 and 30Re respectively, remotely monitor plasma acceleration due to lobe flux dissipation. THEMIS is complementary to MMS and a science and a technology pathfinder for future STP missions.

The FDAB is supporting the University of California in the design, development, integration, test, and launch of THEMIS. Specifically, the FDAB is consulting in the areas of attitude/orbit control and determination, autonomous navigation, and GN&CD systems.

[Technical contact: Mark Beckman]

3.9 Venus Sounder for Planetary Exploration (VESPER) Discovery Proposal

The Flight Dynamics Analysis Branch of the GSFC Guidance Navigation and Control Center is supporting a Venus orbiter Discovery Proposal, Venus Sounder for Planetary Exploration (VESPER), being led by the Goddard Space Flight Center's Planetary Systems Branch. VESPER will integrate key measurements with atmospheric models to investigate the coupled processes of chemistry and dynamics in the Venus middle atmosphere; the goal being to conduct a tightly focused study of the Venus atmosphere as part of a larger NASA program of comparative planetology. VESPER consists of a spacecraft and an atmospheric entry probe and will nominally launch in 2008. The Flight Dynamics Analysis Branch has analyzed launch vehicle requirements, generated nominal trajectory data, and analyzed potential probe impact locations for a 2008 launch.

[Technical contact: Greg Marr]

3.10 General Orbit Determination Error Analysis

The Flight Dynamics Analysis Branch of the GSFC Guidance Navigation and Control Center is supporting a range of orbit determination (OD) error analysis studies for future and current space missions. In the last year, orbit determination error analysis has been performed in support of the Triana, Constellation-X, and Gravity Probe-B (GP-B) future missions. The capability to model TDRSS differenced one-way Doppler tracking data was recently added and has been used to analyze critical early orbit support of the Galaxy Evolution Explorer (GALEX) mission and to analyze a 48 hour tracking campaign to generate precise orbit determination solutions in support of the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission.

[Technical contact: Greg Marr]

3-11 Integrated Mission Design Center (IMDC)

http://imdc.gsfc.nasa.gov/

The Integrated Mission design Center (IMDC) is a human and technology resource dedicated to innovation in the development of advanced space mission design concepts to increase scientific value for NASA and its customers. The IMDC provides specific engineering analysis and services for mission design and provides end-to-end mission design products.

Engineers from the FDAB provided analysis and design support to the IMDC's customers in the areas of Attitude Determination and Control (ACS) and Flight Dynamics. ACS products included requirement definition, identification and computation of significant worse case disturbance torques, sensor selection, actuator sizing, component placement specification, control modes design, identification of ACS imposed requirements on other subsystems, risk assessment, issues, concerns and future work identification. In addition, special design consideration and analysis were performed to solve or pinpoint each mission's unique issue. Many of these innovative solutions were synthesized to meet the need for high precision requirements in L2 and formation missions. Flight dynamics products included trajectory design and the computation of trajectory-dependent quantities needed by other subsystem engineers.

Among the studies conducted, 7 were for near Earth orbit, 1 was a multipart study for geosynchronous orbit, 9 were for trajectories near L2, and 1 was for lunar orbit. Among these, five involved formation flying.

In the past year, ACS and Flight Dynamics IMDC personnel have contributed to improving the design process with new tools and design methodologies. Much of this was accomplished by taking advantage of the breadth of experience found within the FDAB. Some new tools are in the nature of utilities and have been made available to the FDAB in general.

[Technical contacts: Paul Mason, Charles Petruzzo]

4.0 Technology Development Activities

4.1 Advanced Mission Design

The ultimate goal of Advanced Mission Design is to develop and integrate improved methods that allow us to design more complex missions and to minimize the cost of flying these missions. From a simple request to reduce the amount of fuel to achieve an orbit or to compute unique trajectories using new mathematical methods, this task aids us in helping spacecraft engineers and scientist to accomplish their goals. From this effort, we incorporate basic components of optimization methods into our mission design software tools. We also add capabilities to directly use a branch of mathematics called dynamical systems. Using these methods, new orbits were established that encouraged science proposals and allowed new missions. Besides designs of single trajectories, this activity also supports a suite of general design tools that enable optimal geometric designs that meet the constraints for Distributed Space Systems (DSS), which have multiple spacecraft in formations.

This work crosses many projects at GSFC and NASA enterprises as it involves all orbit types, many spacecraft, and provides for new technologies. A portion of this work was a continuation of the Goddard Mission Services Evolution Center (GMSEC) and Earth Science Technology Office (ESTO) funded activities for applications to both Earth and Space Science Enterprises (ESE and SSE). The Technical Readiness Level (TRL) of the research varies, as some optimization techniques are clearly understood but how we should best apply them to orbit design is not. Recent successful optimization analysis has been performed in support of the Global Precipitation Measurement (GPM) constellation, the Solar Dynamics Observatory (SDO) orbit transfers, and the Laser Interferometer Space Antenna (LISA). The LISA formation and control optimization consists of three spacecraft flying 5 million kilometers (km) apart in the shape of an equilateral triangle.

This work helps satisfy the charter of GSFC to reduce the cost of access to space, provide innovative technologies, build capabilities, and transfer this knowledge to the academic and commercial communities. The technical investigations and developments further support the resident expertise particularly within the context of libration point orbit analysis, transfer trajectory design, and general formation establishment and maintenance. The work enhances the theoretical understanding of the multi-body problem and offers the advantages available by incorporating the dynamical relationships into formation flying design. The models and techniques developed provide immediate results for mission support, thus enhancing GSFC participation in proposals while expanding capabilities.

The Advanced Mission Design work described here covers flight dynamics areas important to all trajectory design. These include optimization of orbits to meet science and engineering requirements while minimizing maneuver impacts, application of new mathematical methods to ensure optimal design, investigation of unique orbit design, and the development of new utilities and algorithms to support GSFC missions.

4.1.1 Optimization

The FDAB researches and develops optimization methods for complex and challenging missions. In light of last year's successes with the initial development of algorithms and general research, this year's approach was planned to complete and validate these activities. This year a utility was developed that runs algorithms as an executive and provides some guidance in the selection of the correct optimization method given the orbit conditions and goals. Improved or new optimization methods continue to be included into this utility.

Primer Vectors and Sequential Quadratic Program: Figure 4-1 shows a Matlab GUI using primer vector theory developed this past fiscal year. The next step is to expand the optimization algorithms to enable all orbit designs, add multiple spacecraft capabilities, add conditional constraints (like shadows and coverage), and to ensure robustness. We improved computational speed by 'Mexing' code and investigated various action sequences to converge to different neighboring trajectories. That is, we have the capability to add simultaneously two impulses, add an impulse before moving the time-of-flight, add internal impulses, and etc.

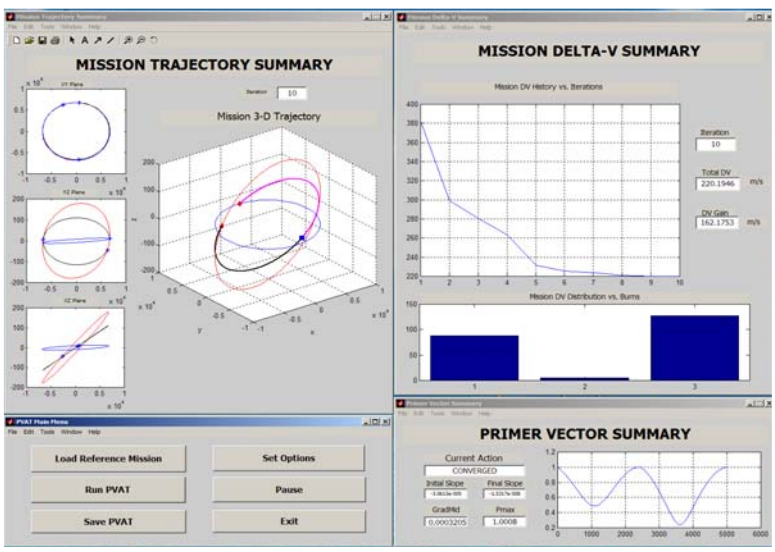

Figure 4-1. Primer Vector Analysis Tool (PVAT)

Optimization Tools: To provide a true capability to ensure the optimal trajectory design we require methods or a set of integrated tools that can perform both mission optimization perform sensitivity analyses in a very general way. It is general in the sense that the analyst can define performance measures, constraints, and independent variables flexibly according to different mission requirements. An approach where the mission sequence can be driven by an optimizer or Monte-Carlo function provides much of this flexibility. Because Matlab is quickly becoming an industry standard for engineering design, it seems an obvious choice to leverage off of its optimization and statistical capabilities. There are many other choices of direct methods that determine if an orbit is

optimal and indirect methods that post-process the orbital data to see if the trajectory is optimal. The goal is to baseline several methods with enough information to allow correct choices for the orbit type, constraints, or engineering aspects (propulsion system, etc.) By permitting a level of generality, we can solve many diverse problems that we currently don't have the capability to solve and vastly improve the time and quality of problems we currently handle. Below is a brief highlight of necessary capabilities that provide a design environment with the desired capability and flexibility:

- Primer Vector analysis using the PVAT utility.
- Sequential Quadratic Programming (SQP) and Projected Gradient Methods
- Genetic Algorithm applications.
- Constrained non-linear optimization for both impulsive and low thrust applications.
- State Transition Matrix propagation to aid in methods or to compute perturbations.
- Linear and non-linear controller capabilities, i.e. acceleration input from a controller for the spacecraft to steer itself on the proper orbit.

Genetic Algorithms: Genetic algorithms (GA) are established methods for the determination of globally optimal conditions that can be used in a wide range of missions. By global, we mean that the orbit or trajectory computed is the best choice. Using this characteristic, we incorporated GA algorithms into our direct methods to ensure a globally optimal solution for minimizing fuel or other orbital conditions. We also considered formation flying mission dependent problems such as, finding the best launching orbit (subject to launch vehicle constraints) that would allow the minimization of fuel to initialize spacecraft in their final operational orbit and formation shape.

4.1.2 Unique Orbits

We analyzed unique orbits using a dynamical system approach. Orbits in the vicinity of the collinear libration points in the Sun-Earth and Earth-Moon systems serve as excellent vantage locations for scientific investigations involving the Sun, planetary, and Earth/Moon environments. We will continue to focus significant development and operations activities for NASA in support of such missions. GSFC missions involving libration point orbits include Constellation-Xray, Maxim, Stellar Imager and James Webb Space Telescope (JWST). The use of multiple spacecraft in a distributed approach to perform interferometry and optical measurements not achievable by a single spacecraft was one of the major drivers in this effort. Trajectory design and pre-launch analysis, as well as on-orbit operations and performance evaluation, for these missions is increasingly challenging as more complex missions are envisioned throughout the upcoming decades.

Orbital Bifurcations: These are the expansion of "typical" libration orbits over an entire region called the weak stability boundary region about any planet. We examined all accessible regions about the Earth and Earth-Moon system. This effort provides orbits to meet unique science requirements that require, for example, dwell times over the poles and low energy transfers. As part of this effort, a branch of mathematics called ***combinatorics*** is being investigated for its applications to trajectory design, and also to the aforementioned optimization methods.

Heteroclinic Connection: We began analysis of the regions for transfers of orbits to the Sun-Earth libration points via the Earth-Moon system. In more detail, there are invariant manifolds (a vast array of virtual winding tunnels and conduits around the Sun and planets) in the Earth-Moon system and similar manifolds in the Sun- Earth/Moon system. Utilizing dynamical systems theory, invariant manifolds associated with solutions in the vicinity of libration points of the Sun-Earth system and of the Earth-Moon system can be easily computed and analyzed. We have been involved with each system individually. Nevertheless, understanding the connections between these two systems is of paramount importance for new mission design. In fact, these new trajectories follow the natural system dynamics and allow the designers to develop new mission concepts to explore different regions of the Sun-Earth-Moon system and beyond. No one has yet established the analytical methods for computing the complete intersection of these manifolds, which can be used to easily transfer a spacecraft from one manifold to another. There is some related work going on in academia but usually it is not to the fidelity required for GSFC use, or it is of an abstract nature and not applicable to orbit design. This work is very important to servicing missions such as JWST.

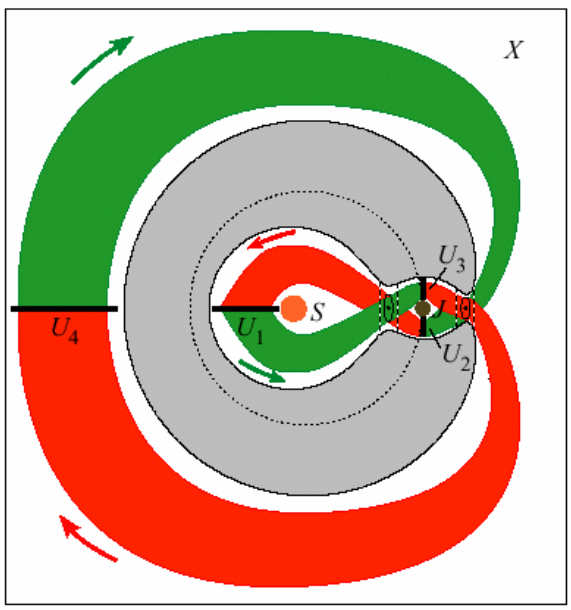

Figure 4-2. Heteroclinic Connection

Dynamical System using 4-body perturbations– Generator: This work involves the upgrades of algorithms to our Generator trajectory design code. The original algorithms developed under this work have provided FDAB with unprecedented capabilities to design libration orbit transfers that are direct. These updates are focused on the application of lunar gravity assist to attain libration orbits, missions routinely supported by FDAB. These updates allow a more efficient and faster method for the computation

of such trajectories. The basic code has been used for JWST and Triana design and will be very useful for all future missions such as Constellation-X and FKSI.

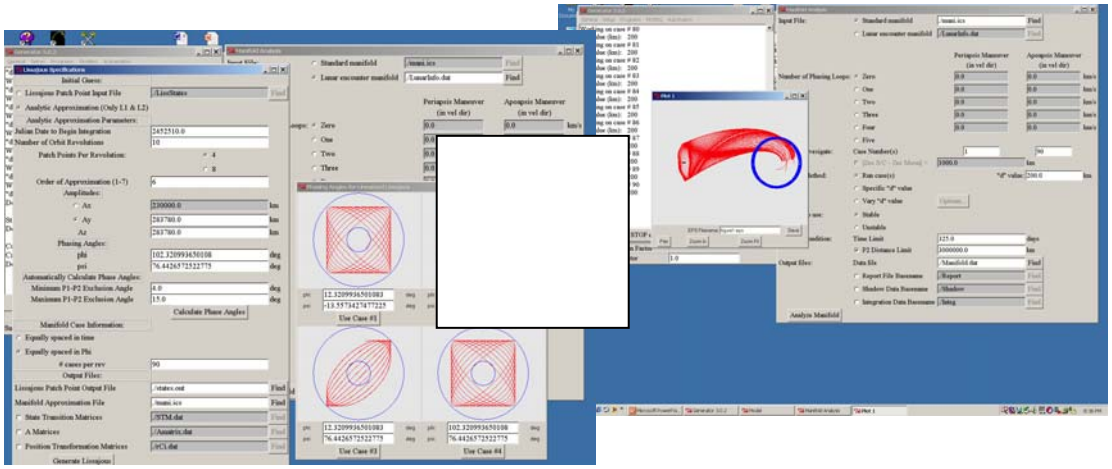

Figure 4-3. Dynamical Systems Utility- Generator

Quasi-stationary locations (***QSLs***): These are locations in the Earth-Sun system that remain relatively stationary and stable over a long period. It is unique in that there is no typical orbital motion like a halo orbit. QSLs have been shown to exist in the analytical and restricted three-body problem. The initial conditions for such locations shows promise and we must now research the control efforts, expand into elliptical restricted motion, use a full ephemeris fidelity, and analyze all the locations about the Earth-Moon system. The work on Quasi-stationary locations is still new (no other center or commercial vendor is performing this analysis) and has only been attempted at GSFC. Some interesting results have been found under last year's effort and will be addressed in a presentation to headquarters Office of Space Science. A method of control was investigated to maintain the orbit near its initial conditions.

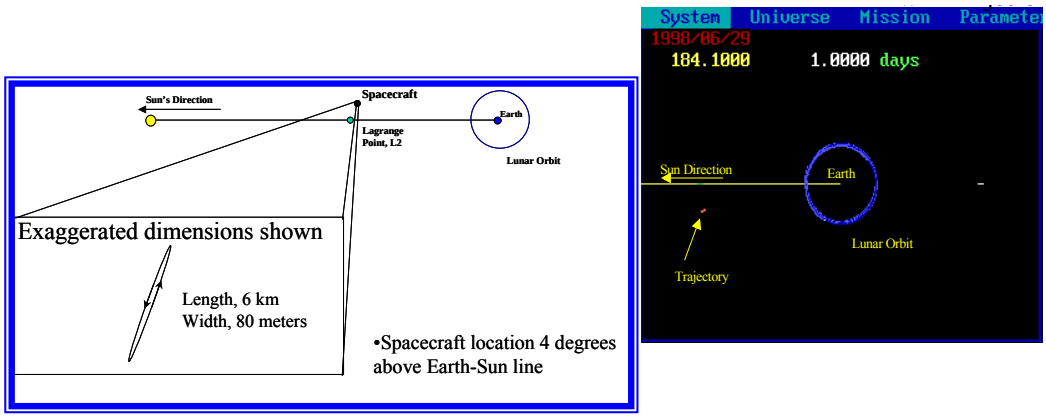

Figure 4-4. Quasi-stationary Locations

4.1.3 Integrators

One arena that benefits from a generic availability of numerical integrators is modeling of multiple spacecraft flying in formation. This is unique in that we developed application algorithms that do not follow the standard thinking when propagating spacecraft (predicting their future orbit). The standard approach is to process multiple spacecraft individually, but in some cases it can be performed more efficiently if we mathematically construct multiple spacecraft orbital data as a single vector.

Single Formation State Propagation: To allow tight formations or formations in locations that have similar perturbations, a method of solving a full state (3 or 6 DOF) to propagate either simultaneously or in sequential fashion as is widely done now was completed. This allows a vast improvement of formation geometry control. There are a number of issues that bear study when modeling the propagation of multiple spacecraft. Among these are the basic approach to integration of such weakly coupled systems, numerical precision issues that arise when the propagation step size is controlled by the most sensitive member of the formation, and issues of efficiency that can arise for either a linked propagation or independent propagation scheme. A key element required for any spacecraft mission design is a precision orbit propagator, designed to match the orbit of the spacecraft. Precision numerical integrators exist in a number of commercially available tools used for flight dynamics planning and operations. These integrators are tightly coupled to the systems that employ their services. Prototype systems that require integration services must either implement the propagation algorithms or make use of an existing system in its entirety in order to model a satellite's orbit.

We developed a suite of spacecraft propagators that share a common, easily integrated application-programming interface (API). The system includes C++ code implementing several Runge-Kutta integrators, a Bulirsch-Stoer integrator, and a predictor-corrector integrator based on the Adams-Bashford-Moulton method. Each of these integrators are designed to work with either a single spacecraft or with multiple spacecraft simultaneously.

[Technical Contact: David Folta]

4.2 Autonomous Navigation Technologies

Autonomous navigation provides highly accurate onboard inertial and relative navigation for multiple satellites. This enables many advanced mission concepts such as formation flying, solar sailing, and low-thrust orbit transfer. It also enhances autonomy for all aspects of mission operations including maneuver planning and execution, communication signal acquisition, real-time onboard attitude determination and control. The FDAB approach maximizes design flexibility by providing a single navigation software system, GEONS, for multiple mission scenarios. The approach optimizes use of available sensor data onboard the vehicles. It reduces mission life-cycle cost for single and multi-spacecraft platforms, by minimizing ground and tracking operations, and by

reducing the development and test cost of autonomous navigation while increasing the efficiency of the navigation process. This year, GEONS Release 1.2 was delivered, which primarily includes new celestial object and intersatellite line-of-sight measurement processing capabilities. This delivery, which includes both the configured flight software and the associated documentation, represents a major milestone in the development of the GEONS flight software.

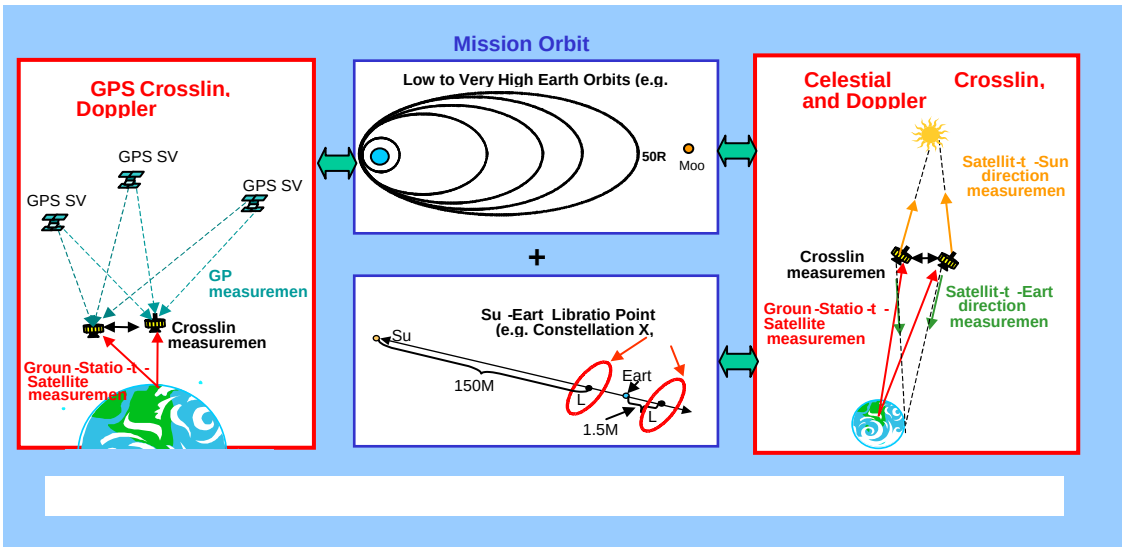

Figure 4-5. Autonomous Navigation Supported by GEONS

4.2.1 Precise Relative Navigation

Options to reduce the GEONS code size for minimal capability DSP-type implementations were implemented. A thorough analysis of options for implementing GPS carrier-phase measurement processing in GEONS was performed. Recommendations were developped for a low-risk, cost-effective implementation approach that should provide a relative navigation capability that meets the requirements of the AFRL TechSat-21 and XSS-11 flight experiments. These experiments will fly GEONS integrated with the ITT Low Power Transceiver.

A technical paper that compares autonomous relative navigation performance for formations in eccentric, medium and high-altitude Earth orbits using Global Positioning System (GPS) Standard Positioning Service (SPS), crosslink, and celestial object measurements was prepared. The paper demonstrates that, for close formations, the relative navigation accuracy is highly dependent on the magnitude of the uncorrelated measurement errors. This paper was presented at the International Symposium on Formation Flying in Toulouse France, October 29-31, 2002.

[Technical contact: Russell Carpenter]

4.2.2 Celestial Navigation

A detailed investigation of the autonomous navigation accuracy achievable for the Constellation-X libration point orbit using only ground-to-spacecraft Doppler measurements was completed. This study indicates that ground-to-spacecraft Doppler measurements are not sufficient to achieve/maintain a stable solution for this orbit using a realistic tracking scenario with realistic measurement errors. Additional analysis was performed of the accuracy that can be achieved using only line-of-sight observations of the Sun, Earth, and Moon. Based on realistic simulations using optical, star-tracker-like, and digital-sun-sensor-like sensor accuracies, the results indicate steady-state accuracies ranging from 10 to 30 kilometers are achievable depending primarily on the magnitude of the sensor biases and the spacecraft attitude errors. Adding in a pseudoangle measurement from North star to the moon significantly improves the accuracy to below 5 kilometers. Relative position accuracies were also investigated using the pseudoangle observations listed above with the addition of intersatellite crosslink range and line of sight observations. These results indicate relative position accuracies on the meter-level can be achieved for a Constellation-X orbit.

[Technical Contact: Cheryl Gramling]

4.2.3 High Altitude GPS Navigation

A study of GPS navigation for future GOES spacecraft was performed. Based on simulations of realistic GPS navigation scenarios that included momentum unloads and East-West and North-South station-keeping maneuvers, it was demonstrated that, if the maneuvers are modeled, GEONS can provide excellent performance both during and following the maneuvers. The GOES system engineering support contractor will use this information to develop the concepts for future GOES missions.

Significant flight data returned from the AMSAT-OSCAR-40 (AO-40) high altitude GPS flight experiment was also analyzed. AO-40, an amateur radio satellite launched November 16, 2000, is currently in a low inclination, 1000 by 58,800 km altitude orbit. Previous experiences with GPS tracking in such orbits have demonstrated the ability to acquire GPS signals, but very little data were produced for navigation and orbit determination studies. The GSFC AMSAT experiment, developed jointly with the GN&CD Components and Hardware Branch, is the first to demonstrate autonomous tracking of GPS signals from within a HEO with no interaction from ground controllers. The receiver has returned a continuous stream of code phase, Doppler, and carrier phase measurements useful for studying GPS signal characteristics and performing post-processed orbit determination studies in HEO. On several occasions when the receiver was below the GPS constellation (below 20,000 km altitude), observations were reported for GPS satellites tracked through side lobe transmissions. Although the receiver has not returned any point solutions, there has been at least one occasion when four satellites were tracked simultaneously, and this short arc of data was used on the ground to compute point solutions.

Three technical papers have been presented covering various aspects of the AMSAT GPS experiment. The first, presented at the AAS Guidance and Control Conference in Breckenridge, CO, described the design of the GPS experiment, and provided some examples of the GPS data returned from the AO-40 spacecraft. The second paper, presented at the AIAA Guidance, Navigation and Control Conference in Monterey, CA, described the initial efforts to generate AO-40 navigation solutions from pseudorange data reconstructed from the GPS receiver's code phase, as well as to generate a precise orbit solution for the AO-40 spacecraft using a batch filter. The third paper, which was presented at the Institute of Navigation's annual GPS meeting in Portland, OR, describes tracking performance, measured power levels from the GPS satellites, and orbit determination analysis based on GEONS processing of the data.

[Technical contact: Mike Moreau]

4.2.4 Magnetometer-based Navigation

Magnetometer based navigation (MAGNAV) provides low cost, autonomous navigation for low Earth orbit (LEO) missions. The magnetometer has four primary advantages. First, it is always part of the sensor complement for LEO missions, primarily for momentum management. Second, it always outputs data; that is, it is not subject to occultation or tracking problems. Third, it is very reliable. Lastly, it provides information on spacecraft attitude, rate, and orbit. The system developed in GN&CD is based on an Extended Kalman Filter algorithm, combined with a pseudo-linear Kalman filter, producing the full set of navigation parameters, namely attitude, orbit, and rate. Reducing the complexity of onboard processing, eliminating costly sensors, and reducing ground operating costs, while providing accuracy and reliability are additional objectives of MAGNAV.

Typically, the MAGNAV algorithm, in order to provide simultaneous attitude, orbit, and rate estimates, also processes data from an additional sensor, such as a gyro, sun sensor, or GPS (operating alone the magnetometer can provide either attitude and rate or orbit estimates). This improves the accuracy and speed of convergence, and ensures robustness. A magnetometer-gyro configuration has been tested with real data from four GSFC satellites. A magnetometer-sun sensor configuration has been tested with data from the TRACE spacecraft. The magnetometer-GPS configuration has undergone analytical testing with the goal of developing a 'black-box' spacecraft navigation system. It is expected that MAGNAV could be used in a backup mode; startup mode, e.g. initialization; anomaly resolution; or as a prime navigation system for a LEO mission with coarse requirements.

Based on the success with TRACE data, an inflight experiment of MAGNAV is planned for the WIRE spacecraft. During FY02, the MAGNAV algorithm was converted from MATLAB code into flight code, as a patch to the WIRE flight software (FSW). Numerous tests have been conducted to verify the conversion, and to ensure the code will run within the FSW attitude control system (ACS) in the onboard computer. The SMEX dynamics simulator was utilized in the testing. Once MAGNAV is successfully patched

into the FSW, the flight experiment will be run for two weeks to test various scenarios of operation, and to verify the onboard performance of MAGNAV.

[Technical Contacts: Julie Thienel, Rick Harman]

4.3 Formation Flying Technologies

Spacecraft formations are a subset of the global collection of multiple spacecraft missions, classified as Distributed Space Systems (DSS). In general a DSS is a collection of 2 or more space vehicles designed to accomplish similar or shared objectives; an end-to-end (information) system consisting of two or more space vehicles, coordinated flight management, and an integrated infrastructure for data acquisition, storage, analysis, and distribution. In contrast a formation is comprised of multiple spacecraft with the ability to cooperatively detect, maintain, and agree on the appropriate maneuver to maintain a desired position and orientation. Formation flying is enabling technology required to maintain the relative separation, orientation, or position between or among the formation spacecraft. The FDAB is pursuing several initiatives, described below, that focus on formation flying technology development.

4.3.1 Autonomous Formation Flying Control of EO-1

NASA's first-ever autonomous formation flying mission is a resounding success. With the launch of NASA's Earth Observer-1 satellite, called EO-1, NASA's Goddard Space Flight Center has demonstrated the capability of satellites to continuously fly in formation, to react to each other, and to maintain close proximity without human intervention. This unique advancement has been highlighted in *Aviation Week and Space Technology* and on space related web sites. The new capability allows satellites to autonomously react to each other's orbit changes quickly and efficiently. It permits scientists to obtain unique measurements by combining data from several satellites rather than flying all the instruments on one costly satellite. It also enables the collection of different types of scientific data unavailable from a single satellite, such as stereo views or simultaneously collecting data of the same ground scene at different angles.

On EO-1, formation flying was required to calibrate and compare technological advances made in ground observing instruments that are smaller, cheaper, and more powerful. Until an onboard algorithm and system were developed at GSFC, the requirements could not be easily met. Previously, satellites did not plan nor execute orbital maneuvers onboard, nor were they equipped to autonomously accommodate the actions of any other satellite in support of a desired scientific experiment. Onboard EO-1 is an advanced technological controller called AutoCon that is capable of autonomously planning, executing, and calibrating satellite orbit maneuvers. On EO-1 it is used for the computation of maneuvers to maintain the separation between the two satellites. The maneuver algorithm is designed as a universal 3-dimensional method for controlling the relative motion of multiple satellites in any orbit. The AutoCon architecture and mathematics were first developed by Aerospace Engineers at the Goddard Space Flight

Center (GSFC). Their idea was then combined with a new flight software that is the commercial predecessor of a GSFC sponsored commercial software called *FreeFlyer*, produced by Lanham, MD based a.i.-solutions, Inc.

This unique onboard demonstration establishes the following NASA capabilities:

- A flight demonstrated, validated, fully non-linear autonomous formation flying system. (A NASA first for continuous formation flying)
- A precision universal control (Folta-Quinn) algorithm with user defined control accuracy that can be used for any orbit.
- A formation flying and orbit maintenance system that allows:
    - Cartesian Control: Alongtrack, radial, and crosstrack
    - Keplerian Control: Semi-major axis, inclination, node, eccentricity
    - Any combination of the above
    - Single or multiple maneuver computations.
- Proven executive flight code that incorporates fuzzy logic for multiple constraint checking for maneuver planning and control.
- Use of text scripts for onboard command control, software changes not required.
- Utilization of various Navigation inputs (GPS, TONS, Ephemeris, etc.).
- Attitude (quaternion) required of the spacecraft to meet the □V components.
- Generation of maneuver commands onboard.
- Calibration of the maneuver onboard.

There are many benefits of this onboard formation flying system. Because maneuver calculations and decisions can be performed onboard the satellite, the lengthy period of ground-based planning currently required prior to maneuver execution will eventually be eliminated. The system is also modular so that it can be easily extended to other mission objectives such as simple orbit maintenance. Furthermore, the flight controller is designed to be compatible with various onboard navigation systems. Onboard formation control enables a large number of satellites to be managed with a minimum of ground support. The result will be a group of satellites with the ability to detect errors and cooperatively agree on the appropriate maneuver to maintain the desired positions and orientations. The formation flying technology flown onboard EO-1 will make distributing scientific instruments over many separate satellites routine and cost effective.

Since this technology is now fully developed and demonstrated, synchronous science measurements occurring on multiple space vehicles will become commonplace and the concept of Earth observing 'virtual platforms' will become a reality. In the process, this technology enables the development of autonomous rendezvous. Scientific payloads could be launched from any launch vehicle, rendezvous with and join a formation already in place, and then autonomously maintain this condition or respond to specific requests for science data collection by altering its own orbit. Thus, this technology addresses all of the NASA directives to build revolutionary satellites.

Application to future NASA GSFC missions is beginning with the decision of the Global Precipitation Measurement mission to fly it for autonomous maneuver control to improve the science predictions of the orbit.

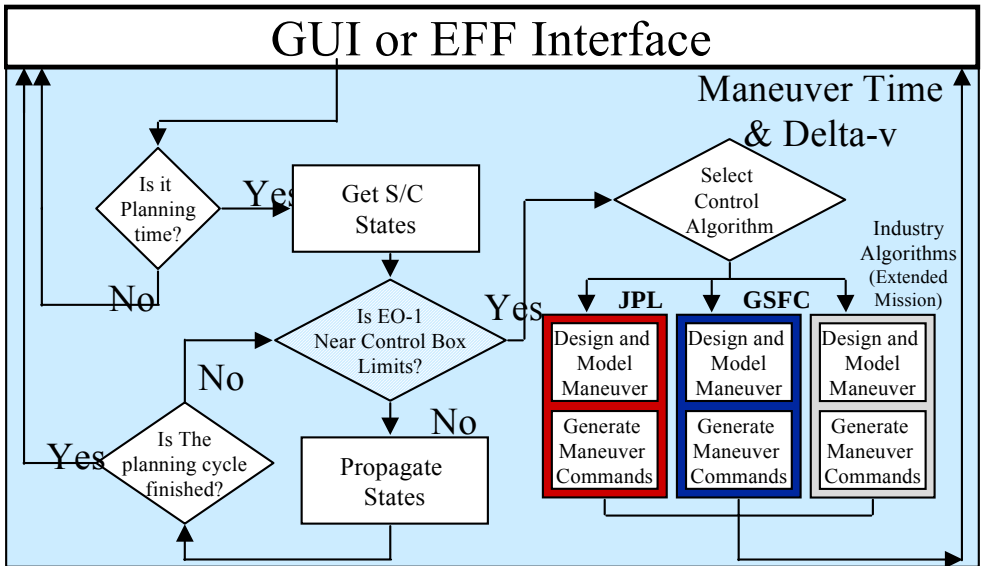

Figure 4-6. AutoCon Control Flow

Code 572's Autonomous Maneuver Control (AutoCon) was selected as a runner-up in the 2002 NASA Software of the Year competition. This marks the 5th year in a row that a Goddard software product has been selected as runner-up or honorable mention for the award. Formation Flying is one of the most exciting concepts permeating NASA today and was enabled by AutoCon for the first autonomous demonstration.

[Technical Contact: David Folta]

4.3.2 Tethered Formation Flying

The Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) is a bold new mission concept designed to address fundamental questions about the Universe, including how the first stars formed from primordial material, and the first galaxies from pre-galactic structures, how the galaxies evolve over time, and what the cosmic history of energy release, heavy element synthesis, and dust formation is. Ideally, a very large telescope with an effective aperture approaching one kilometer in diameter would be needed to obtain high quality angular resolution at these long wavelengths, however this approach proves to be too expensive and therefore impractical. Instead, a spin-stabilized, tethered formation is one possible configuration being considered requiring a more advanced form of formation flying controller, where dynamics are coupled due to the existence of the tethers between nodes in the formation network. To this end an investigation into the dynamics and control of multiple tethered spacecraft systems was launched.

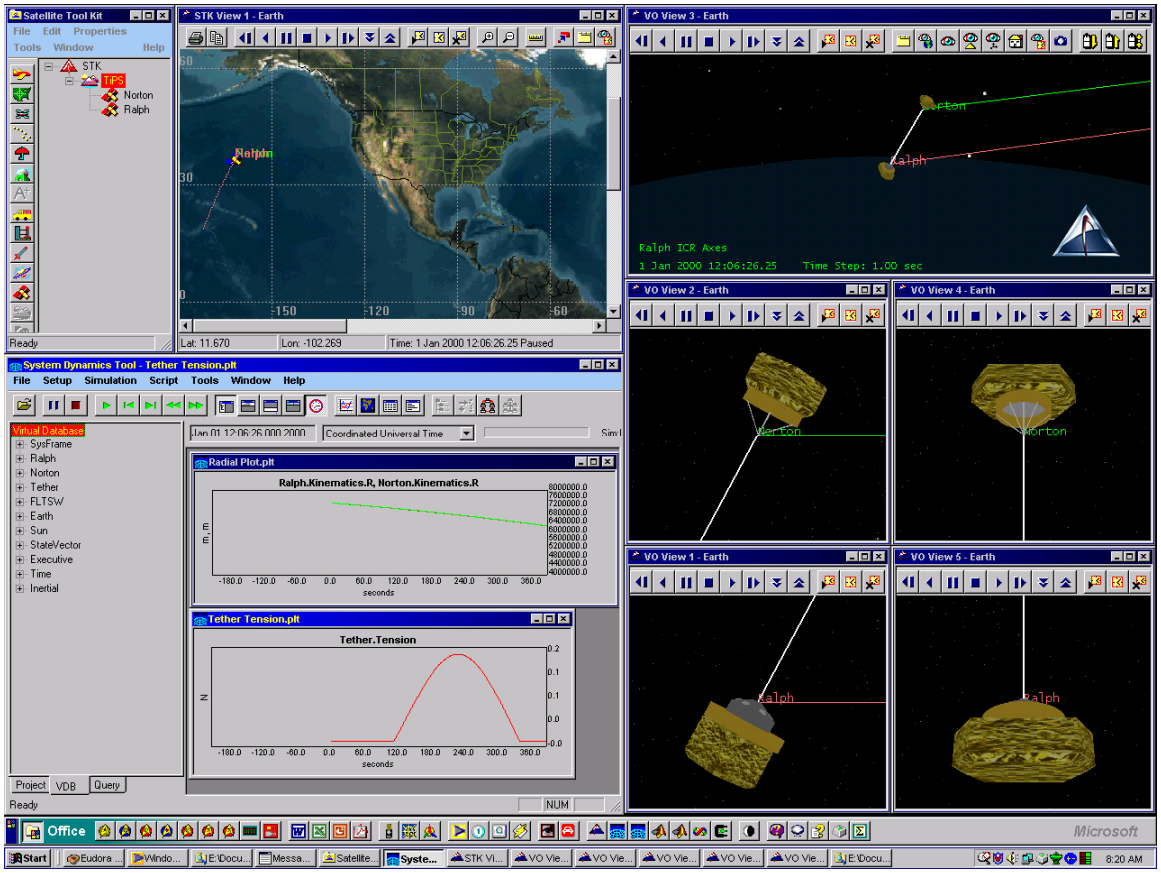

Figure 4-7. Tethered Formation Flying Satellite Dynamics Tool (SDT) – Satellite Tool Kit (STK) Connection

The effort is divided into three separate tasks. Task-1 involves working with mission scientists in an effort to understand and document the science requirements of a SPECS class facility. GSFC science and optics specialists are working with engineers from Payload Systems Inc. (PSI) and the Naval Research Laboratory (NRL) to capture the science requirements and flow those down to understand the engineering requirements imposed by the desired science. Using the Generalized Information Network Analysis (GINA) framework developed at the Massachusetts Institute of Technology, PSI will then conduct detailed configuration trade studies. Many possibilities will be examined in an effort to conduct a "broad-brush" analysis so as to get an understanding of the favorable regions in the trade space and suggest candidate configurations capable of meeting the science requirements.

Task-2 involved cooperation of GSFC with engineers at NRL in the development of the equations of motion for a rotating multi-tethered system applicable to the study of fundamental dynamic characteristics of a deep space interferometer concept. The system is assumed to be comprised of n-particles inter-connected by any number of tethers in a user defined configuration. The concept system is intended to execute planar rotation, to deploy and/or retract the tethered masses, and be capable of re-orienting the spin axis. Accordingly, the mathematical model allows full three dimensional motion of all the

constituent elements. At this writing all masses are all assumed to be 3-DOF particles and a model involving 6-DOF finite masses is under development. The NRL model can be used in either of two modes. In one mode, the user specifies the forces to be applied to the particles and the resulting dynamics are computed. This is the standard means of implementing controls. To aid in the development of control laws for such a complicated system, as second mode was designed into the dynamics model. In this mode, the desired dynamics are prescribed by the user and model outputs the forces necessary to give rise to that motion. It is believed that this capability will aid controls designers in their efforts.

NRL's n-particle dynamics model has been implemented into Star Technologies Satellite Dynamics Tool (SDT) application which in turn interfaces to Analytical Graphics Satellite Tool Kit (STK) application. The result is a system which allows the user to construct n-particles inter-connected by m-tethers in any user defined configuration. SDT will then use the imbedded NRL model to compute the dynamics of the particles, generating ephemeris data that is handed over to STK for 3D graphical output.

Working with the Virginia Tech, Task-3 is examining key linear and non-linear control methodologies which may prove applicable to the problem of tethered formation flying, specifically gain-scheduled controllers, Lyapunov based non-linear controllers and/or robust adaptive controllers. The object was to build upon the dynamic development from Task-2 in order to create a core dynamics and control model which permits iteration and expansion while maintaining the primary thrust of the tethered formation. The ultimate goal for this task is to develop a set of control laws centered on the core model from Task-2. This will serve as a first order tool for examining the dynamics and control of a variety of design configurations.

Finally, as the project comes together the configuration trades will narrow the trade space identifying at least one candidate configuration which can be examined in greater detail. A model of the candidate configuration will be constructed in the SDT application using NRLs dynamics model. Virginia Tech's controls will be imposed on the dynamics and a comparison made to the original requirements for scientific success. In this way we will have constructed an important capability and taken a crucial step towards making a SPECS type mission a real possibility.

4.3.3 6DOF Nonlinear Control for Formation Flying

Virtual platforms, based on spacecraft formations, form the strategy for improving the spatial and angular resolution achievable for space-based observatories. Stellar Imager, and the Micro-Arcsecond X-ray Imaging Mission (MAXIM) are typical missions based on this design concept. Precision formation flying falls among the enabling technologies required for mission feasibility and success. The section describes current research related to control algorithms for precision formation flying. The specific area of research considers the problem of simultaneous control of a spacecraft's orbit and attitude, in order to meet the strict mission requirements (micro-arcsec pointing, and sub-millimeter position control).

Spacecraft orbit and attitude trajectories are governed by nonlinear dynamics, and combined allow for six degrees of freedom (6DOF) in motion. Research targets the development of a 6DOF, nonlinear control algorithm for achieving the design specifications for missions requiring precision formation flying. Algorithm development is based on the assumption that these missions will be stationed near the L2 point in the Earth/Moon – Sun system. Hence, the orbital dynamics are characterized by the restricted-three body problem. Further external disturbances are limited to solar pressure, and other gravitational sources. To date the approach has been proven to work for relative position control. Accomplishments are published in several papers, noted in the references below. Current work is focused on incorporating attitude control into the position control algorithm, generating a full 6DOF solution.

For further information, refer to the following:

1. Luquette, R. J. and Sanner, R.M. "A Non-Linear Approach to Spacecraft Trajectory Control in the Vicinity of a Libration Point", Flight Mechanics Symposium, Goddard Space Flight Center June 19-21, 2001.

2. Luquette, R.J. and Sanner, R.M. "A Nonlinear Approach to Spacecraft Formation Control in the Vicinity of a Collinear Point", AAS/AIAA Astrodynamics Specialist Conference, 30 July – 2 August 2001, Paper No. AAS 01-330.

3. Luquette, R.J., Leitner J., Gendreau, K., and Sanner, R.M., "Formation Control for the MAXIM and MAXIM Pathfinder Missions", Proceedings of SPIE Astronomical Telescopes and Instrumentation Conference, 22-28 August 2002.

[Technical contact: Rich Luquette]

4.3.4 Maxim Pathfinder Testbed

The FDAB provided engineering support of the Maxim Pathfinder X-ray Interferometer test bed. Activities included the design and fabrication of a precision double-slit and mirror control system used to focus an eighty meter long x-ray interferometer beam onto a five millimeter CCD detector with sub-arcsec, sub-micrometer accuracy. The computer control system provides a real time, hardware-in-the-loop foundation with general applicability to the integrated Formation Flying test bed. Specifically, the new system addresses the FFTB's need for a real time simulator with the capability to interface with numerous GN&C and instrument subsystems. The current incarnation of the system utilizes a dual processor computer control and data handling architecture, but was design to be N-processor scalable in order to accommodate future scenarios with large number of spacecraft and/or complex interface requirements.

[Technical contact: Steve Queen]

4.3.5 Decentralized Estimation and Control of Distributed Spacecraft

Decentralized control is an appealing approach to maintaining satellite formations for several reasons. It is non-hierarchical, so that coordination by a central supervisor is not required, but it retains the optimality of centralized control. Each satellite need only process its own local measurement data, in a form of parallel processing. Detected failures degrade system performance gracefully. For a given level of system reliability, a decentralized architecture may be cheaper to build, since the individual spacecraft can be built with much lower individual levels of reliability than the supervisor satellite in a centralized architecture.

This research has been ongoing for several years, and is highlighted in the FDAB, End of Fiscal Year 2001 Report. Research has focused on investigating implementation issues and testing in a relevant environment. Testing activities have augmented existing resources at Goddard with those at the University of California at Los Angeles (UCLA), the Naval Postgraduate School (NPS), and the Massachusetts Institute of Technology (MIT) through appropriate arrangements.

[Technical contact: J. Russell Carpenter]

4.4 Attitude Determination

4.4.1 PiVoT Attitude Determination

The PiVoT GPS receiver provides position, velocity, and time using GPS. The objective of this work is to make attitude available from PiVoT. Attitude is determined as a solution via a minimum mean-squared estimate (MMSE) of the nine parameters in the 3x3 attitude matrix. Thus as many satellites as are currently being tracked can be used to improve the attitude estimate. Two methods are being made available for making the resulting 3x3 matrix a proper orthonormal attitude matrix: cross products of columns (speed) vs singular value decomposition (accurate, but slower). The MMSE approach allows each attitude solution to be independent of previous ones (as opposed to using small angle approximations as has been done for SIGI on the International Space Station). The attitude solution can be expected to handle higher rotation rates than does SIGI.

The attitude solution runs both double-differencing and single-differencing algorithms in tandem. Single differencing requires that the "line bias" parameters (effectively time delays between antenna centers and the receiver) be known, whereas double-differencing uses one additional satellite to cancel out the need for knowing the line bias. There are two costs to using double-differencing: one more satellite needs to be tracked and a 40% noise increase (due to the subtraction of two Gaussian noise variates). The difference in the single and double difference solutions is used to estimate the line bias; once the line bias settles down, the single difference solution is presented as the better solution.

The Landis algorithm for obtaining attitude from two satellites has been incorporated into the PiVoT attitude determination software. Thus double-differencing attitude estimates can be obtained from tracking only three satellites and, if line biases have been determined, single-differencing attitude estimates obtained from only two satellites. The use of this algorithm is completely transparent. As a caveat, note that the primary position-velocity-time estimates requires four satellites. When the number of tracked satellites drops to three satellites, the onboard time can be used to determine position and velocity. When the number of tracked satellites drops below three, GPS receivers on satellites use an orbit model to estimate its position. Since the attitude in earth-centered earth-fixed coordinates depends on where the satellite is relative to earth, such attitude estimates will exhibit a growing error.

The attitude determination software depends on the use of phase differences of the incoming signals on the different antennae (interferometric approach). Since the antennae are likely to be farther apart than a wavelength of about 18cm, there remains an integral ambiguity in the number of wavelengths between the antenna along the signal path. Integer ambiguity resolution is done using Iz, Ge, and Chen's grid point search algorithm. The approach taken allows some constant rotation during the resolution process, and involves singular value decomposition and considerable matrix manipulation and so the process is numerically intensive. Once the integer ambiguities are determined, the current attitude solution is used to solve for the integer ambiguities for newly tracked satellites.

[Technical Contact: Charles E. Campbell, Jr.]

4.4.2 GPS Attitude Sensor

A novel Global Positioning System (GPS) sensor concept is under development that would provide data for both navigation and attitude. The Compound Eye GPS Attitude and Navigation Sensor (CEGANS) would be equipped with multiple directional antennas mounted on the convex hemispherical surface. Each antenna would be aimed to receive GPS signals from a restricted, but known visualization cone. By noting which GPS satellites are visible in the field of view of each antenna in the hemispherical array, the attitude of the sensor (and therefore the body to which it attached) can be estimated to within 3 degrees without resorting to the use of carrier-phase measurements. It is believed that optimization and signal-to-noise techniques can be applied to refine raw attitude estimates from this compact sensor to the sub-degree range.

A simulation study is underway which is beginning to prove the CEGANS concept can work. To date, the sensor is given perfect measurement data and so yields perfect solutions. As this idealized simulation is degraded to more closely replicate the true environment (addition of noise models etc.), a more realistic performance expectation can be formulated. Here again, Star technologies Satellite Dynamics Tool (SDT) is proving invaluable in providing the vehicle in which the entire GPS constellation can be modeled

as well as the RF interfaces to the satellite employing the CEGANS sensor. A patent on the CEGANS is expected to be issued by the end of this calendar year.

[Technical Contact: Dave Quinn]

4.4.3 Advanced Attitude Determination Methods

A new star identification algorithm was developed which uses the Expectation Maximization (EM) method. EM consists of two steps. First, the log of the probability density function is formed and the expectation computed. Second, the argument is found which maximizes the expectation. A star field was simulated in which the observed stars are rotated 20 degrees away from the reference stars. The EM algorithm was used to identify the observed stars and to calculate the rotation angle.

This algorithm was applied to the following cases of star distributions: the number of observed stars is identical to the number of reference stars, the number of observed stars is less than the number of reference stars, and the initial uncertainty in the rotation angle was as large as 40 degrees. The next step is to apply this algorithm to observed mission star patterns as processed by our operational star identification system.

Nutation can be a significant problem for any spinning spacecraft. Most recently, the IMAGE spacecraft had a nutation problem that was the result of an undersized damper. The problem was solved by using the torquer bar to fight the nutation during each perigee. A technique has been developed to estimate nutation angle. Data was simulated for a spacecraft rotating at 7 RPM with a nutation angle of 5 degrees and a nutation rate of 9.5 degrees/second. Figure 4-8 shows the true sun angle relative the spacecraft spin axis as well as the observed sun angles. The final result of the algorithm compared perfectly with the nutation angle.

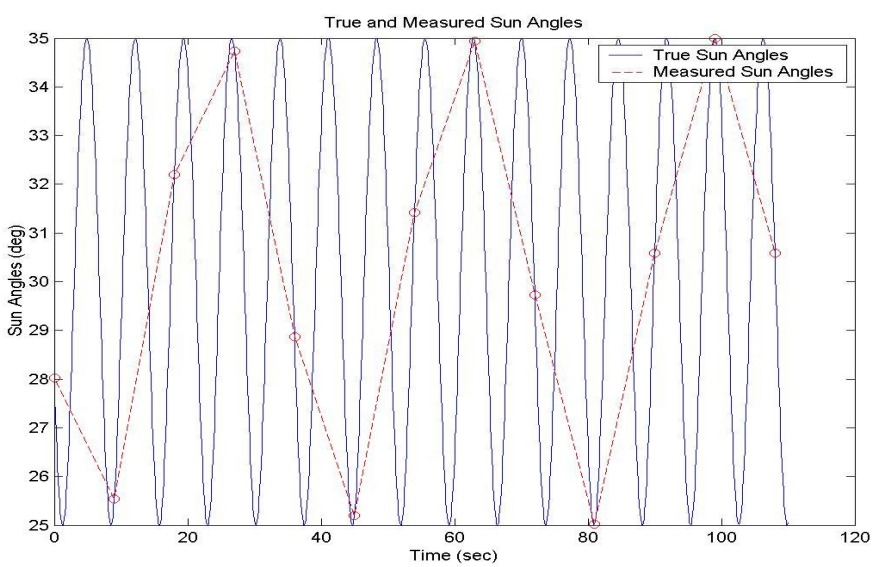

Figure 4-8. True and Measured Sun Angles for a Nutating Spacecraft

A pseudo linear Kalman Filter was developed to estimate gyro model misalignments, scale factors, and bias for a triad gyro configuration normally used in spacecraft. A simulation was set up to model the gyro errors and a maneuver about the spacecraft x, y, and z axes. Applications for this algorithm include real time gyro calibration on the ground as well as onboard the spacecraft. Further work will include adding the gyros as a measurement, testing with flight data, and incorporating the system into the Mission Three Axis Stabilized Software (MTASS) system.

[Technical contact: Rick Harman]

4.5 Flight Dynamics Automation Studies

4.5.1 Flight Dynamics Automation with The University of Maryland

The University of Maryland Department of Aerospace Engineering has continued to act as a test bed for researching ground system automation techniques for the SAMPEX mission. Work completed to date includes the pre-processing and uploading of tracking data, as well as the initial release of a Web based Graphical User Interface (GUI). A report titled "SAMPEX Orbit Determination Automation Plan" was released. Work continues on the following: parallel testing of old and new systems; improvement of user interface; enhancement of tracking data conversion methodology; orbit determination based on tracking data; post-processing of orbit determination results into various products and sending the products to their intended recipients. Planned work includes the following: complete the development of a graphical user interface accessible through a web browser which will allow a user to observe the status of the process, obtain the latest results, and modify the products produced to include where certain products should be sent to, as well as when this should occur. This will be done so as to automate the current manual process as add flexibility to address future products. (University of Maryland SAMPEX Link: http://kepler.umd.edu/sampex/)

[Technical Contact: Joseph Toth]

4.5.2 TRMM Reengineering

The Flight Dynamics Analysis Branch has also partnered with the Mission Applications Branch (NASA GSFC Code 583) and a.i. solutions in order to support TRMM Reengineering activities. This work is being undertaken using the development of the Autonomous Flight Dynamics System (AutoFDS). Work completed to date includes the additional development and enhancement of the AutoFDS, as well as participating in various meetings, presentations, and demonstrations of the AutoFDS. Work continues on the following: further enhancements of the AutoFDS in order to support TRMM Reengineering activities which includes product definition, user interface improvements, and the addition of capabilities such as file event based execution to the current system. Planned work to be carried out under the GSFC Mission Services Evolution Center

(GMSEC) includes further TRMM Reengineering activities as well as the integration of the AutoFDS with the AutoProducts System, and the definition of XML based messages.

[Technical Contact: Joseph Toth]

4.6 Nanosat Technology

The Guidance, Navigation, and Control Division (GNCD) has assumed management and systems engineering oversight of two existing formation flying nanosatellite missions being developed at MIT, Cornell University, Utah State University, and Virginia Tech. Emphasis has been placed on usage of proper flight-certified materials to comply with shuttle flight safety standards and detailed analysis efforts to determine the proper dispensation system to use for ejection from the shuttle bay. The GNCD is also overseeing the systems integration and shuttle safety preparation process with prime support from Orbital Sciences Corporation, in preparing these missions for a potential 2003 or 2004 shuttle launch. Further, GNCD is leading an effort to help Goddard Space Flight Center and the Air Force Research Laboratory (AFRL) extend their partnership from a personnel exchange, facilitating the collaboration on mutual technology and research interests, to developing an education and outreach "hands-on" program designed to teach and direct the aerospace technology systems engineering process at the undergraduate and graduate level engineering curriculum. The intent is to reach a greater volume of universities and their students possessing varied expertise in experiment and flight hardware development. With the challenges of space access ever present, both agencies will share the task of formulating a pathway to increase flight opportunity and encourage flight demonstrations targeting the goals and needs of future missions.

[Technical Contact: Lucien Cox]

4.7 GMSEC Architecture Development

The Goddard Mission Services Evolution Center (GMSEC) is envisioned as a ground system architecture of the future that will provide mission services such as mission planning, scheduling, data processing and command management to flight projects. The rationale behind establishment of the GMSEC architecture and supporting functions is to help retain and extend expertise at Goddard in ground systems and operations, and provide a focal point for the development of mission services related technology and ground system upgrades. Mission services functions include several flight dynamics activities usually required in ground support of flight projects. These include attitude determination, ground attitude control, attitude sensor calibration, orbit determination, and orbit maneuver planning. As part of its support to current flight projects under development, the FDAB works to define and implement software systems required for flight dynamics support. The FDAB will also be an active participant in GMSEC architecture development activities. During the past year, the branch participated in

architecture planning activities and proposed mission services technology projects for FY03.

[Technical contact: Thomas Stengle]

5.0 Branch Infrastructure

5.1 Flight Dynamics Tool Maintenance

An active software tool maintenance and development program is required by the FDAB to perform future mission studies, flight project mission analysis and operations support. In doing so, this effort supports the maintenance, use, and administrative activities associated with the FDAB institutional flight dynamics tool suite in response to the needs of FDAB engineers.

FDAB tools consist of a combination of homegrown systems, commercially available products, and extensions to commercially available products developed and/or procured in support of FDAB flight dynamics engineers. The flight dynamics tools support the following activities within the FDAB: attitude error analysis, prediction and determination; navigation, orbit error analysis, orbit prediction and determination; and mission analysis, trajectory design and maneuver planning. This tools maintenance effort also provides the navigation technology engineering support necessary to maintain the official releases of the GPS Enhanced Orbit Determination (GEODE) and GPS Enhanced Onboard Navigation System (GEONS) flight software, and support integration of GEODE and/or GEONS with one or more space receivers or satellite flight computers.

Specific tasks performed under the Flight Dynamics Tools Maintenance task included:

- Sustaining engineering support for FDAB institutional flight dynamics tools
  - maintained core expertise associated with FDAB institutional flight dynamics tools
  - provide analysis concerning the implementation and use of FDAB institutional flight dynamics tools
  - define and conduct maintenance activities associated with FDAB institutional flight dynamics tools
  - configuration management and system administration support associated with GNCD institutional flight dynamics tools

- Maintaining an inventory of institutional tools
- Generating and maintaining the FDAB flight dynamics tools Maintenance Plan
- Delivering upgrades to institutional flight dynamics tools in response to the Maintenance Plan

During the past year the REPEAT utility was converted from Fortran to MATLAB, using a language translator that was developed during FY01. Also, a paper was prepared that provides the details for strategies to maximize the probability of star identification using the Attitude Determination Subsystem (ADS) contained within the Mission Three-Axis Stabilized Spacecraft (MTASS) with minimum initial attitude information. Under this effort, we also documented all the .m (MATLAB) files in a searchable database. The major area of concentration during this past year has been to develop a graphical user interface (GUI) for the General Maneuver (GMAN) Program, and to integrate new

propulsion system modeling into the GMAN Program, thus greatly enhancing the versatility of the software tool. Additionally, the GUI could be adapted for use by other flight dynamics software tools (e.g. ACQSCAN) fairly easily. On-going support for GEODE/GEONS software engineering was also provided.

In-house FDAB engineers worked during the past fiscal year to maintain and enhance major ground-based navigation systems such as the Goddard Trajectory Determination System (GTDS). Major work includes:

- Place identified systems (and versions) under software configuration control by the GNCD Lab
- Build optimal systems from different versions in the UNIX platform (these optimal systems will become official GNCD navigation systems)
- Port all GNCD ground-based navigation systems to PC platforms
- Develop a user friendly interface for PC versions of GNCD ground-based navigation systems
- Add technical and graphical capabilities to PC versions of GNCD ground-based navigation systems
- Perform research and analysis to improve performance and optimize operational use of ground-based navigation systems to support future missions (e.g., as backup systems in formation flying in case of failure of onboard navigation systems).

The delivery of GNCD Release 2.1 and a partial delivery of Release 2.2 have been completed. Release 2.1 consists of 24 orbit related systems including the following:

1. GTDS PC Version - This is equivalent to the FDF HP-UNIX Release 2000.02 of GTDS.
2. INITTVHF - This utility allows the user to create and initialize a Trajectory Computation and Orbital Products System (TCOPS) Vector Hold File (TVHF) for use with GTDS.

The partial delivery of Release 2.2 includes the following systems:

1. TLE2ELE - NORAD 2-Line Element to ELCONV format Conversion Program
2. TLE2NEP - NORAD 2-Line Element to NORADEP format Conversion Program

Work continues on GNCD Release 2.2 of GTDS, which will consist of a port of the HP-UNIX Operational Release 2001.01 of GTDS to the Windows environment. GNCD Release 3.1 was also started, and planned for delivery in January 2003. It includes the following modifications: capability to use geopotential models of up to 360x360 in size, including the complete EGM96 geopotential model; capability to use EGM96 enhanced earth tide model; and the capability to use central bodies other than the Earth, Moon, or Sun.

In addition, the development of a sophisticated user interface and graphics capabilities for GTDS is in progress with the support of Code 583 software engineers.

[Technical Contacts: Son Truong, Joseph Toth, John Lynch]

5.2 Guidance, Navigation and Control Lab

The Guidance, Navigation and Control Lab (the Lab formerly known as the Flight Dynamics Analysis Lab) under the oversight and management of the Flight Dynamics Analysis Branch continued to provide a state of the art computing environment for both the FDAB engineers and the GNCD engineers. Consolidation of the computing domains was complete in FY02 and new domain servers were put online. These servers increased the online storage capacity to several terabytes. In addition, a new tape backup system was put online. This new tape backup system increases backup capability to nine terabytes and gives improved performance and expandability. New user workstations were added to the lab that provide the engineers with increased computational capability and allow for major analysis projects to be completed in a more timely manner.

The GNC Lab hosted several classes and demos in FY02. Hosting classes for the COTS engineering tools used by FDAB and division engineers allows them to receive training on the systems they will use to run the software.

The GNC Lab also provided operations support during several International Space Station (ISS) EVAs.

[Technical Contact: Sue Hoge]

5.3 Flight Dynamics Models

5.3.1 SKYMAP Maintenance

The SKY2000 Master Catalog (MC) stellar database is the starting point for SKYMAP mission star catalog generation, and is also used in many non-SKYMAP systems developed by the astronomy/space science community. The SKY2000 MC contains ~300,000 entries, is complete to ~8 visual magnitude (Mv) with some entries fainter than Mv = 10. The current MC was developed and refined using the best data from multiple star catalogs. Improvement in the quality and quantity of MC data is a continuous process as new catalogs are released, more star tracker data are collected and existing data are incorporated.

An important capability of the SKY2000/SKYMAP System is the prediction of instrumental passband magnitudes (Mi), principally star tracker magnitudes for space missions using the Multi-Mission Star Catalog (MMSCAT) generation software. Missions currently using SKYMAP star catalogs include: RXTE, SWAS, Terra, Aqua, Landsat-7, GOES I-M, UARS, SOHO, and ACE.

The SKY2000 Task operates under a limited budget, so yearly improvements to the MC and MMSCAT software are moderate and must be prioritized. Two activities completed this year include an update to the SKYMAP Web page and some improvements to the MMSCAT executable to enhance near-neighbor/magnitude blending subsystems. See the link above to the SKYMAP Web page for general information on the SKY2000 MC, MMSCAT, and to download the entire SKY2000 MC or selected mission catalogs and delivery memoranda.

Task personnel attended the Star Catalog Working Group meeting at USNO (Washington, DC) in January 2002. They led a discussion group on star catalogs and software tools. The task lead was nominated as co-chair of a working group examining issues involving a single, centralized star catalog for the various user communities.

Task personnel also provided consultative support in response to questions regarding the SKYMAP Master Catalog and related issues, and in response to questions regarding star catalog/star tracker issues faced by current and upcoming missions (including RXTE, Aqua, ACE, Landsat-7, and Swift).

Visit the website: http://mmfd.gsfc.nasa.gov/prod_center/pc_frame_page.htm

[Technical contact: David Tracewell]

5.3.2 Solar Flux Predictions

The FDAB continued to support periodic updates of the Schatten solar flux predictions. These predictions are used for future mission analysis and for decay studies of operational missions.

Solar activity during 2002 has been slightly higher overall than predicted by the Schatten nominal solar flux activity predictions (Figure 5-1). This plot shows the actual solar activity (the jagged line) along with the –2 sigma, nominal and +2 sigma prediction curves (bottom, middle and top smooth curves) for 2001 & 2002. While the measured solar activity was lower than predicted (centered on the –2 sigma curve) for the first 9 months of 2001, there was a sharp increase in activity in the Fall of 2001, from ~160 to 225 F10 Radio Flux. The solar activity level continued to be more than the +2 sigma prediction for approximately 6 months, but has decreased and is currently centered on the +2 sigma prediction curve, and is trending towards the nominal prediction. It should be noted that the Schatten solar flux predictions are not meant to capture these short-term variations, and are used as a more general trending tool for long-term predictions. However, the increase in predicted solar activity did cause low-Earth satellite orbits to decay more quickly than the preceding year.

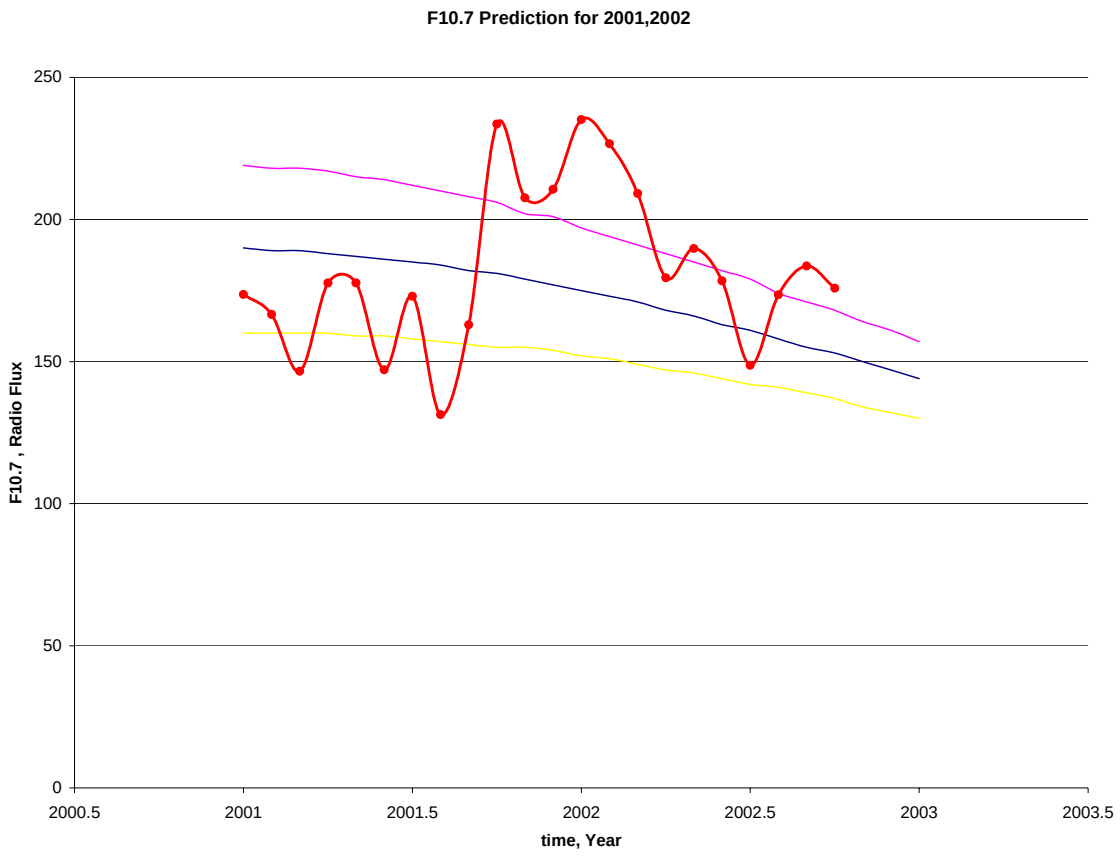

Figure 5-1. Predicted and Actual Solar Activity for 2002, 2002

[Technical Contact: Karen Richon

5.4 FDAB Website

During this FY, branch members worked to refurbish the FDAB website. Information was added concerning all of the missions currently being supported by the branch. Information on typical analysis provided to customers as well as on our tool suite and major research areas is now documented on the site. Pictures of branch members were updated, and news items were added. Current and past End-of-Year reports are available, as well as a partial reference list of the papers published by branch members. Future capability for a searchable database of published papers is planned for next fiscal year.

Visit the FDAB website at: http://fdab1.gsfc.nasa.gov/

[Technical Contact: Sue Hoge]

6.0 Interagency Activities

6.1 X43-A Failure Investigation

Hyper-X is a NASA multi-year hypersonic flight research program seeking to advance the state of the art through air-breathing hypersonic flight. The goal of the Hyper-X program is to flight validate key propulsion and related technologies for air-breathing hypersonic aircraft. The program consists of three X43 vehicles, which will fly at speeds of Mach 7 and 10. Each of the vehicles is 12 feet long with a wingspan of about five feet (see figure). The first X43 and its modified Pegasus-XL booster rocket was launched on June 2, 2001 at about 1:43 p.m. from NASA's B-52 launch aircraft flying at about 24,000 feet altitude. The flight was terminated when a major malfunction occurred about eight seconds into the boost phase, causing the X43-A vehicle to lose control. At that point, a decision was made to terminate the flight. In support of the failure investigation board, FDAB personnel provided support in: (a) multi-rate analysis of the autopilot, and (b) assessing Monte Carlo and perturbation analyses.

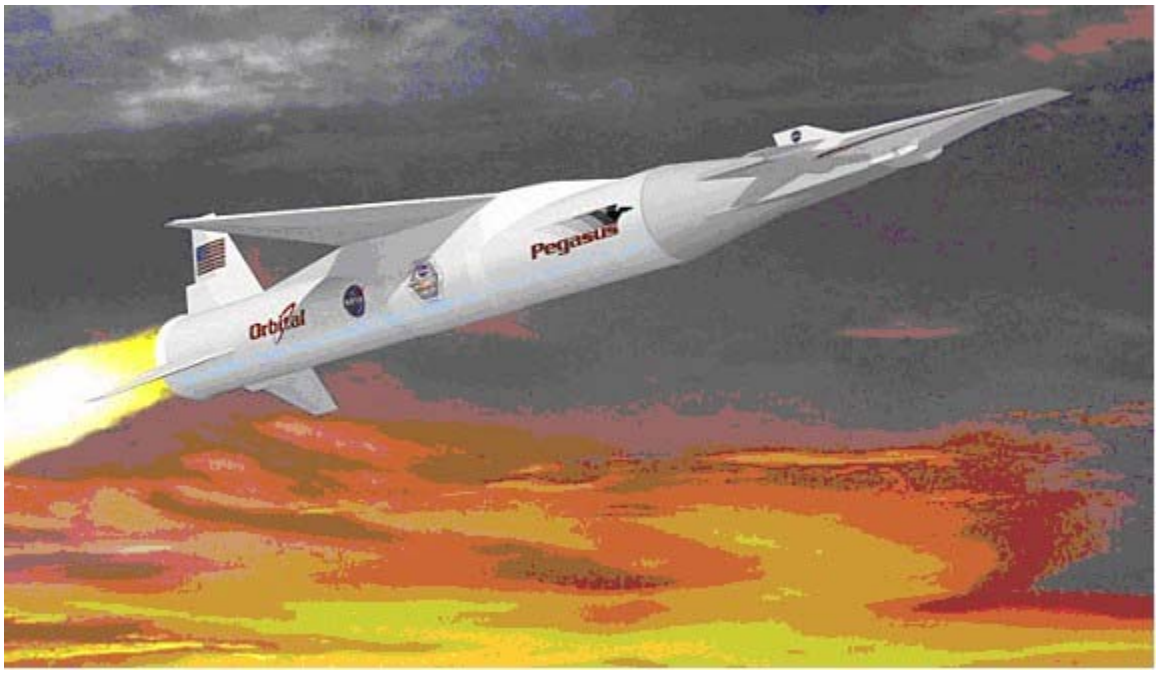

Figure 6-1. X-43 Air-Breathing Hypersonic Aircraft

The OSC's Autopilot lateral and longitudinal design and linear analysis models were examined. Specifically, the continuous-time implementation of a 100-Hz digital bending rate filter in the analysis was flagged for further investigation. The autopilot's main loop ran at 25 Hz, hence a need for multi-rate analysis. An analytical multi-rate implementation of the filter within the autopilot loop was formulated and verified via an independent MATLAB simulation. The multi-rate formulation was also validated via independent SIMULINK simulations. The analytical multi-rate formulation was provided to the Hyper-X team for future implementations.

An assessment of the adequacy of the pre-flight Monte Carlo analyses, stress tests, and sensitivity analysis were made. Parameters, parameter variations, distributions, and correlations in several key areas (aerodynamics, Fin actuation System, and GN&C) were investigated for adequacy. Additional parameters to be included in the return to flight analyses were identified and reported.

[Technical Contact: Peiman Maghami]

6.2 SCISAT

SCISAT is Canada's first science satellite in over 30 years. The mission is to study the Earth's upper atmosphere ozone layer, predominantly over Canada. As the spacecraft orbits the Earth, there is a Sun rise and Sun set every 90 minutes. During those events, the spacecraft uses the Sun light cutting through the upper atmosphere to measure the ozone levels.

Due to the very long time between missions, the Canadian Space Agency (CSA) invited the FDAB attitude control experts to review its design. With concurrence from NASA Headquarters, the review was held in Winnipeg Canada. Bristol Aerospace presented its design as well as its development flow. The FDAB experts commented on the design and concentrated on the integration and testing process. Both Bristol Aerospace and CSA engineers found the meeting to be very helpful. The senior ACS engineers from Bristol Aerospace and FDAB continue to stay in contact, receiving updates and giving advice. SCISAT is scheduled to launch in January 2003.

[Technical contact: Dave Mangus]

6.3 NASA Technical Standards Program

http://www.ccsds.org/
http://standards.gsfc.nasa.gov/

The FDAB supports the NASA Technical Standards Program by contributing to the work of the GSFC standards program, the NASA Data Standards Steering Council (DSSC), and the Consultative Committee for Space Data Systems (CCSDS). The GSFC standard program aims to expand the scope of best practices, and to develop an agency-endorsed database of preferred technical standards for NASA. The Data Standards Steering Council (DSSC) is the hub of the NASA Data Systems Standards Program and is sponsored by NASA Headquarters. The Consultative Committee for Space Data Systems (CCSDS) is an international organization of space agencies interested in mutually developing standard data handling techniques, to promote the interchange of space mission support information.

The CCSDS Sub-Panel P1J is specifically chartered to investigate and recommend navigation data standards. P1J has a membership representing several international agencies. The main task of P1J is to develop preferred standards for the exchange of navigation data. The work of P1J is accomplished primarily at workshops, conducted at least twice a year, at facilities coordinated by the hosting member agency. The fiscal year 2002 workshops were conducted at the European Space Research and Technology Center (ESTEC), Holland, and the European Space Operations Center (ESOC), Germany, facilities of the European Space Agency (ESA), in October 2001 and April 2002, respectively.

Accomplishments: The P1J navigation team completed a status review of the green book (technical report), titled "Navigation Definitions and Conventions", officially released for distribution in July 2001, but did not identify any updates; and a second CCSDS-wide review of the red book, titled "Orbit Data Messages" (ODM), which proposes a recommendation for space data systems standards for the exchange of spacecraft orbit information. This red book is expected to be approved by all CCSDS member agencies for promotion to blue book status (accepted preferred standard) by the end of calendar year 2002. P1J completed a set of questions pertaining to spacecraft identification specifications and tracking data interface requirements for CCSDS-wide responses, for work on future recommendations. ESOC and JPL conducted a successful test to verify proper exchange of the ephemeris (EPM) format, using the Ulysses spacecraft, in preparation for their support of the ROSETTA and Mars Express missions in 2003. P1J also prepared a poster to advertise the ODM development at the SpaceOps and International Telemetering Conferences. Both events are scheduled for October 2002. Future work of P1J will involve developing new technical reports and recommendations for navigation data exchange in the areas of tracking, attitude, time services, environmental models and astrodynamic constants, and proximity operations.

[Technical contact: Felipe Flores-Amaya/572]

7.0 Employee Development Activities

7.1 New Employee Profiles

During FY2002, the Flight Dynamics Analysis Branch welcomed three new employees.

John Van Eepoel started in the Flight Dynamics Analysis Branch at Goddard Space Flight Center on September 30, 2002. He received a B.S. in Aerospace Engineering from the University of Maryland in 2000, going on to earn his S.M. from M.I.T. in the fall of 2002. His work at M.I.T. focused on fault detection and repair for spacecraft, culminating in his thesis titled "Achieving Real-time Mode Estimation through Offline Compilation". His work at Goddard has taken him in a new direction. His current work includes supporting the JWST mission with analysis of the attitude control system, and molding the branch's attitude estimation system, MTASS, to the TRMM mission. In the future, John hopes to advance the attitude estimation systems used on the ground and on-board spacecraft, and in the process gain mission experience by implementing these systems for the control centers.

Oscar Hsu has been working with the Flight Dynamics Analysis Branch since September 9, 2002. He received his B.S. and M.S. in Aerospace Engineering from the University of Maryland, College Park and the title of his M.S. thesis was "Effect of Inlet Enthalpy on Liquid-Fueled Active Combustion Control." He is currently working on developing an 18 degree-of-freedom nonlinear SIMULINK model for the ST-7 mission, which will be used as the validation model for the controller used in the disturbance rejection system.

Bo Naasz joined the Flight Dynamics Analysis Branch on July 1, 2002. Bo received his Bachelor's and Master's Degrees in aerospace engineering from Virginia Tech, where he specialized in vehicle dynamics and control. Bo's M.S. thesis title was "Classical Element Feedback Control for Spacecraft Orbital Maneuvers." He is currently working on autonomous guidance, navigation, and control for spacecraft and spacecraft formations, including simulated and GPS hardware-in-the-loop studies.

7.2 Professional Intern Program

The Professional Intern Program (PIP) is a Goddard developmental program for entry-level scientists, engineers, and administrative professionals. Within the FDAB it is an important development program for new engineers, designed to acquaint them with NASA and GSFC missions and operations, integrate them into the workforce as quickly as possible, and prepare them for more complex and responsible duties that they can perform with increasing independence. There are two levels of participation within the program. Employees entering with a BS degree begin in Level I and graduate into Level II following completion of Level I requirements and their first promotion. New employees entering Goddard with an MS degree begin in Level II. Required program activities include the establishment of a mentor relationship with an experienced staff member, various orientation activities, formal and on-the-job training, and completion of

a PIP project, which the intern describes in a written report and oral presentations given in Levels I and II to a panel of evaluators. During the past year, four PIP projects were completed and presented. A description of each of these PIP projects (prepared by each intern) is given below.

PIP Level I Project: The Effects of Deployment and Sun Acquisition on the ST-5 Constellation (Melissa Fleck)

My PIP Level I presentation, entitled "The Effects of Deployment and Sun Acquisition on the ST5 Constellation," was successfully completed on December 7, 2001. The Space Technology 5 (ST5) mission is composed of three 25 kg class spacecraft, each controlled by a single, offset maneuvering thruster. One of the early requirements of the mission was that at any point during the mission, over a two-hour span centered at apogee, the three spacecraft were to be separated by no less than 100 km and no more than 1000 km. Because the spacecraft have a small amount of fuel and no closed loop constellation maintenance, the major concern was how to get the spacecraft into a constellation that would limit spacecraft drift. My project was to determine the best method of spacecraft deployment and sun acquisition so that the constellation would not drift apart during the three-month mission lifetime.

In order to determine the best deployment and sun acquisition method, I created a Matlab simulation that modeled the spacecraft deployment and sun acquisition maneuvers. I then ran a Monte Carlo simulation that varied the three unknown parameters: spacecraft launch date, right ascension of the ascending node, and true anomaly. In all of the simulations run, sun acquisition was performed immediately after spacecraft deployment.

The original deployment plan for the ST5 spacecraft called for the launch vehicle to be despun, and the spacecraft deployed simultaneously from the launch vehicle approximately 120 degrees apart. From the results of the Monte Carlo simulation, it was clear that a constellation deployed in such a fashion would drift apart very quickly. An alternative deployment plan that was proposed had the launch vehicle rotate 120 degrees between spacecraft deployments such that each spacecraft was deployed along approximately the same vector. According to the results from my Monte Carlo simulation, this method of deployment yielded the best initial constellation formation. Upon the recommendation of the GNC team, the ST5 project adopted this method of spacecraft deployment.

(Missie Fleck has been a Goddard employee since July 2001. She received her BS degree in Mechanical Engineering from the University of Maryland. She is currently pursuing an MS degree in Aerospace Engineering from the University of Maryland)

PIP Level I Project: ST5 Orbit Definition and Constellation Control (Anne DeLion)

This project accomplished two goals for the ST5 project: it defined the ST5 mission orbit by determining the lowest initial perigee that would allow the spacecraft to maintain a minimum altitude over the mission lifetime, and it studied the possibility of maintaining a

mission-required separation between the ST5 satellites by taking advantage of differences in the satellites' drag profiles.

Thermal concerns required ST5 to maintain at least a minimum altitude of 200-km throughout the entire mission. The initial perigee altitude had to be high enough to accommodate altitude fluctuations due to orbital perturbations. Satellite Took Kit (STK) analysis showed that the lowest allowable initial perigee was 270-km to maintain the minimum lifetime perigee height.

ST5 originally required a separation that was greater than 100-km but less than 1000-km between any two satellites near apogee. Using the idea that a difference in drag force between two ST5 satellites could be used like a ΔV maneuver, this project preliminarily showed that separation between two ST5 spacecraft could be controlled using small attitude maneuvers to change the cross-sectional area of one spacecraft with respect to another.

(Anne DeLion has been a full time Goddard employee since July 2001. Prior to that time, she was a coop student within the branch. She received her BS degree in Aerospace Engineering from Purdue University)

PIP Level II Project: An Application for Sizing Momentum Wheels and Magnetic Torquer Bars on Spacecraft (Kristin Makovec)

During this year, I completed my PIP Level 2 project, which was titled "An Application for Sizing Momentum Wheels and Magnetic Torquer Bars on Spacecraft." The project resulted in the development of a Matlab application which performs preliminary sizing for momentum wheels and magnetic torquer bars by examining a worst case condition of three-axis stabilization. The developed application is general for all non-spinning spacecraft and is adaptable for various missions. A GUI (Graphical User Interface) is available with the application to allow for a user-friendly method of data entry and is shown in Figure 7-1.

The GUI contains options which vary parameters to allow for multiple runs or Monte Carlo simulations, as well as giving the user the option to choose which environmental torques are included. In addition, there are choices in the method of data entry for certain environmental torques, and the option to perform slew calculations. Default, save, and load capabilities are available on the GUI. The application runs through Matlab and calls upon a Simulink model to perform the calculations. The results are displayed graphically and in a table of maximum required values. A users manual is available with the application.

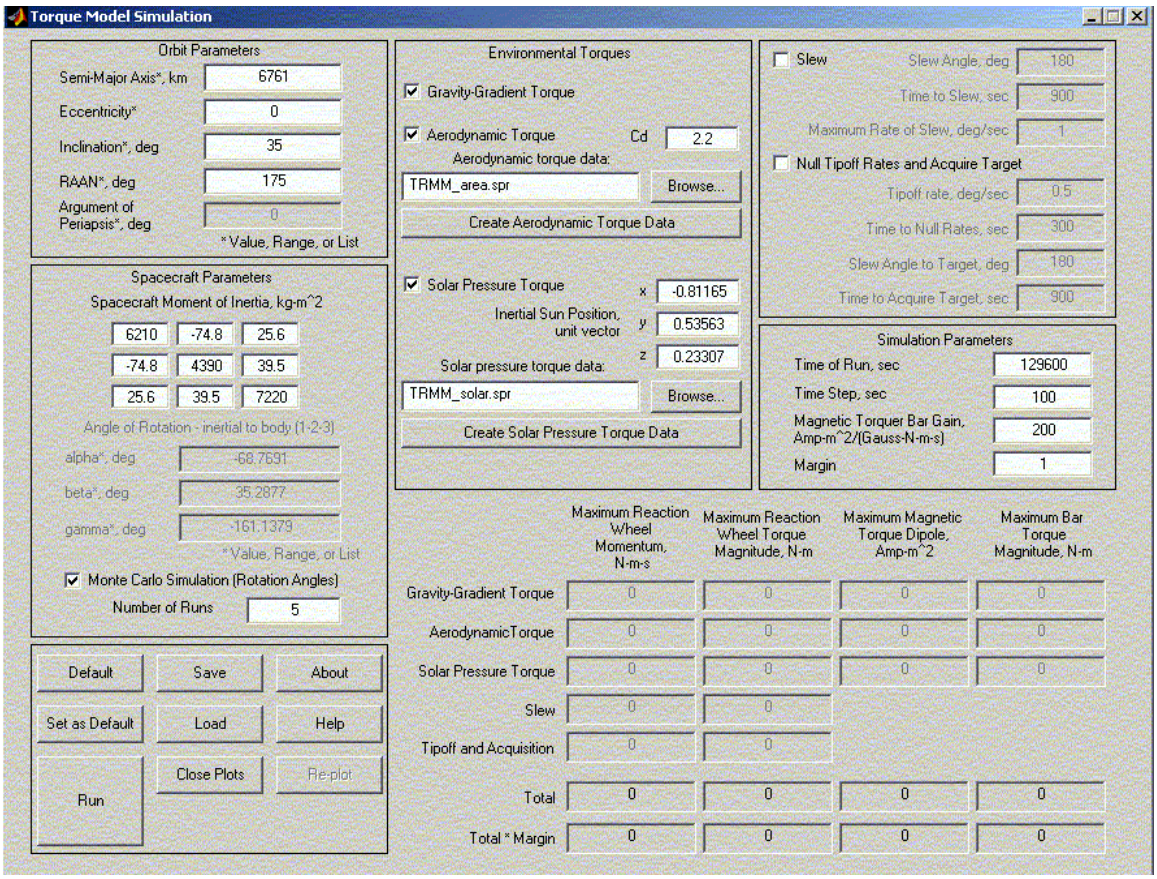

Figure 7-1. Momentum Wheel Sizing Utility

The application was verified by comparing generated results with TRMM (Tropical Rainforest Measurement Mission) data. After verification, the application was used for the preliminary wheel sizing of SDO (Solar Dynamics Observatory) and wheel and torquer bar sizing of GPM (Global Precipitation Measurement). The results from the simulation runs were provided to the analysis teams for each of the missions.

(Kristin Makovec has been a Goddard employee since August, 2001. She received her BS and MS degrees in Aerospace Engineering from Virginia Tech)

<u>PIP Level II Project: A Two-Wheel Observing Mode for the Microwave Anisotropy Probe (Scott Starin)</u>

The Microwave Anisotropy Probe (MAP) launched successfully in June, 2001, with a mission to map the Cosmic Microwave Background. A complete first mapping of the sky was completed after the first six months (the minimal mission length), and continuing observations improve upon those measurements.

MAP was designed under a philosophy of "selective redundancy" to keep mass and hardware costs relatively low. As a result, MAP has only three reaction wheels—the minimum required to complete its nominal mission. In the event of a wheel failure, however, the mission should be completed in a degraded mission mode. My PIP project was to explore options that would allow the mission to continue with as little impact to science observations as possible.

Before I started work, Dr. Tom Flatley had suggested that MAP, if it suffered a wheel failure, could be given an angular momentum bias using thrusters and that the two active wheels could be used to stabilize and control the natural motion. The resulting combination of nutation and spin would then provide a useful, though degraded, observing scan pattern for the fixed microwave instruments.

My main contribution was to design a stable algorithm to control nutation angle by calculating wheel commands based on sensor inputs already available to the Attitude Control software; the design used existing software table structures to allow for on-orbit adaptability. I also aided in the design and development of algorithms to be used during the critical thruster maneuvers of the early operations period and during the establishment of a momentum bias for two-wheel observations. Software development and testing was done in two phases so that mission-critical elements would be available before launch; the final software products are ready to be uploaded in the event of a MAP wheel failure.

(Scott Starin has been a Goddard employee since October, 2000. He received his BS degrees in Aerospace Engineering, Physics, and Multidisciplinary Studies from N.C. State and his MS degree in Aerospace Engineering from Ohio State.)

7.3 Cooperative Education Program

The Cooperative Education Program is an important link in the educational process that integrates college level academic study with full-time meaningful work experience. This is achieved through a working agreement between GSFC and a number of educational institutions. This agreement allows the students, through study and work experience, to enhance their academic knowledge, personal development, and professional preparation. Additionally, Co-op employees earn income that is based on the level of education and work experience they have attained. The FDAB fully supports the Goddard Co-op program and many of its full time employees were former Co-ops. In FY2002, three Co-ops worked in the branch. Given below are descriptions of their work experiences.

<u>Aaron Cooper (University of Minnesota)</u>

During this past summer I worked on a variety of different projects. The first was deriving the equations for the gravitational force of center bodies of different geometries on a point mass. Dave Mangus and John Lynch oversaw the work I did in this area. The second project I worked on was a study to determine whether it was possible to obtain the mass of the fuel remaining on the Tropical Rainforest Measurement Mission (TRMM)

spacecraft. The idea here was to use flight data and the dynamics of the spacecraft to obtain an equation that could solve for a single variable describing the geometry of the fuel. Using this variable we would subsequently determine the mass of the fuel on-board. This method turned out to be too sensitive to changes in the value used for the force being exerted by each thruster. My mentor for this project was Stephen Andrews. The third thing I worked on was assisting Paul Mason in some analysis of the induced torque caused by the migration of the Center of Mass on the Solar Dynamics Observatory (SDO) spacecraft, and how different thruster configurations could reduce the magnitude of the induced torques. Finally, I spent a good chunk of time this summer working on the testing and verification of a PC version of the Interactive Controls Analysis (INCA) software developed by John Downing. I worked on comparing the results of INCA with those produced by MATLAB for a number of simple transfer functions. I also built up the TRMM delta-V control system that was previously developed by Stephen Andrews, and analyzed it in INCA and MATLAB. These results were also compared with the results of Steve's previous analysis, which was done on the VAX version of INCA. Stephen Andrews was my mentor on this project and I also worked with John Downing on the software issues surrounding INCA.

Rivers Lamb (Virginia Polytechnic Institute and State University)

The summer of 2002 was my fourth co-op tour with the Flight Dynamics Analysis Branch. My primary assignment during this time was to learn about geosynchronous mission design, specifically in support of the Solar Dynamics Observatory (SDO) spacecraft. This project was conducted under the guidance of Bob DeFazio, and included learning both ascent optimization and engine modeling programs. The ultimate result of this work was a possible mission profile for the ascent maneuvers to the mission orbit based on a launch in August 2007. This work included such considerations as ground station coverage and stationkeeping requirements. I also supported a trade study investigating the options for the ascending node of the orbit based on obscuration of the high gain antennas. Finally, this work led to support of the geostationary GOES-R mission during the time it was in the Integrated Mission Design Center (IMDC). Working alongside Bob DeFazio and Charlie Petruzzo, this included the selection of the geosynchronous transfer orbit as well as an analysis of the requirements for station changes.

Leigh Janes (Purdue University)

Over my ten week tour this past summer, I worked on two different projects. The first was to begin constructing a toolbox in Matlab for trajectory design and mission analysis tools. Steven Hughes was my mentor for this project. For the toolbox I took existing Fortran code and interfaced it with Matlab using mex functions established in Matlab. I worked on Fortran mexing for converting Keplerian elements to circular elements and for a two-body propagator. My second task was to learn the process used for designing geosynchronous missions. For this project I worked with Robert DeFazio. In order to learn this process I looked at the orbit planning for Solar Dynamics Observatory (SDO).

I modeled maneuvers for the spacecraft, from launch vehicle separation to orbit placement. I also planned station keeping maneuvers to allow the spacecraft to remain within the drift box.

7.4 Professional Development Program

http://www.hq.nasa.gov/office/codef/codeft/pdp/

The Professional Development Program (PDP) is designed to broaden the participants' knowledge and understanding of the Agency and encourage the development of their leadership skills through a combination of expanded work experiences and formal training. Participants in this program, who are competitively selected at each Center and then across the Agency, identify developmental work assignments away from their home Center. Benefits include learning new job skills, being exposed to new areas of NASA and senior NASA officials, and participating in a variety of developmental activities.

Dr. James O'Donnell, a senior Aerospace Engineer in the Flight Dynamics Analysis Branch, is participating in the PDP from August, 2002, through July, 2003. His primary work assignment is in the Office of the Chief Engineer at NASA Headquarters, and he is hoping to arrange a collateral work assignment at either the European Space Research and Technology Centre (ESTEC) or the Jet Propulsion Laboratory (JPL).

[Contact: James O'Donnell]

7.5 In-house Employee Classes

Technology transfer is a key element in sustaining a well-trained work force. The FDAB encourages all engineers to take advantage of the many training opportunities that Goddard has to offer. In augmentation with the Goddard training, the FDAB is continuing to offer courses that are developed in house and taught by the senior engineers. These courses are targeted for the new engineer, yet other senior engineers who wish to expand their field are encouraged to attend. Three of the more prominent courses are listed below:

The "Attitude Control Systems for Non-ACS Engineers" course was designed as an introduction for the new engineer who has only a scholarly background in control systems. The course expanded on how to apply their knowledge to the real world design of attitude control systems. All classes, with guest lecturers and hardware demonstrations, were video taped for future use.

Dr. Bar-Itzhack, who was under a NASA grant from the Technion-Israel Institute of Technology, presented the "Attitude Estimation and Kalman Filtering" course. The course covered the basics of attitude determination, Kalman filter design and then the combination of the two for attitude estimation.

The “Kane’s Method for Solving Multi-body Dynamics” course presented a method of solving multi-body dynamic problems in a cleaner way than the more conventional methods. The course covered Kane’s basic theory as well as how to use the AUTOLEV software. The participants were assigned homework that involved setting up the problems on paper and using AUTOLEV to produce dynamic equations of motion.

[Technical contact: Dave Mangus]

7.6 Attitude Control System Handbook

The FDAB has drafted a document from which an ACS subsystem may be conceptualized, designed, validated, and supported throughout all mission phases. It includes both programmatic and technical guidelines to be used throughout the life cycle of such a development, and is based upon a combination of in-house experience, NASA input, recent red-team guidelines, and outside resources.

This document is not intended to be a control systems design and development class. It is assumed the subsystem engineer using this document is well versed in control theory and in the use of simulation. For example, the use of Bode or Nichols plots is not discussed, however, design guidelines pertaining to criteria to apply to these tools is covered. The Swales Corporation was contracted to work with the senior ACS engineers within the FDAB, and capture their philosophies within the document.

[Technical contact: Dave Mangus]

7.7 TableSat

TableSat is an interactive, single axis hardware simulator that physically demonstrates the reaction of attitude control systems. Using a simple radio communications link, the table is controlled by a laptop computer. A gyro package and set of fans are mounted on a 1.5 foot diameter table that is suspended on a centered pin. Also on the table are coarse sun sensors, a receiver, transmitter and batteries. The laptop, containing SIMULINK, is outfitted with a receiver and transmitter set. This system allows the user to ‘fly’ the table. Any control system can be modeled and modified in SIMULINK resulting in a real-time reaction of the table. The table was developed as a demonstration tool for the “Attitude Control Systems for Non-ACS Engineers” Course. Due to the very positive feedback from the class participants, the table is to be expanded to demonstrate areas including flexible body dynamics. A storyboard will also be developed to create interest in attitude control systems at conferences and universities.

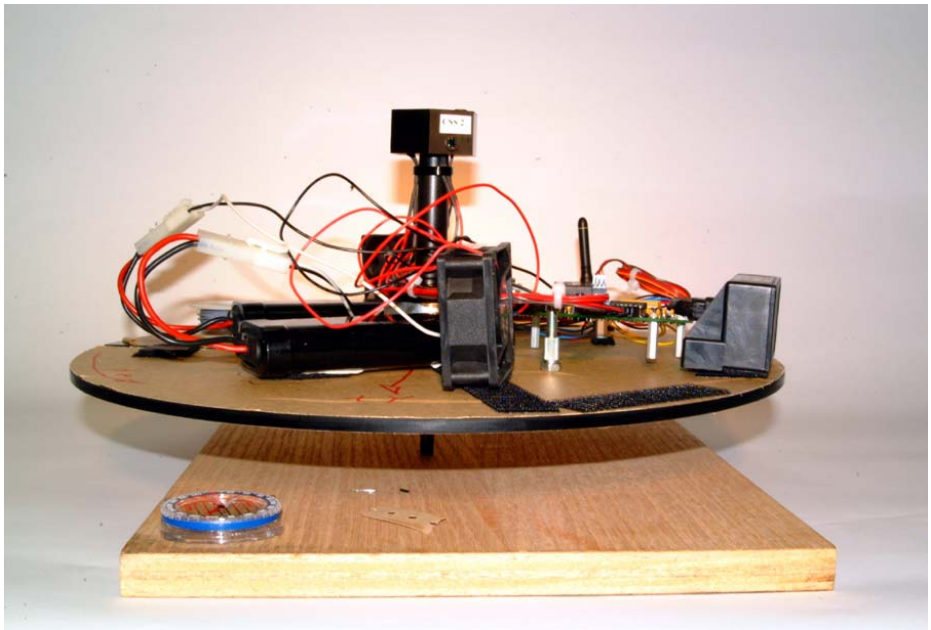

Figure 7-2. TableSat Side View

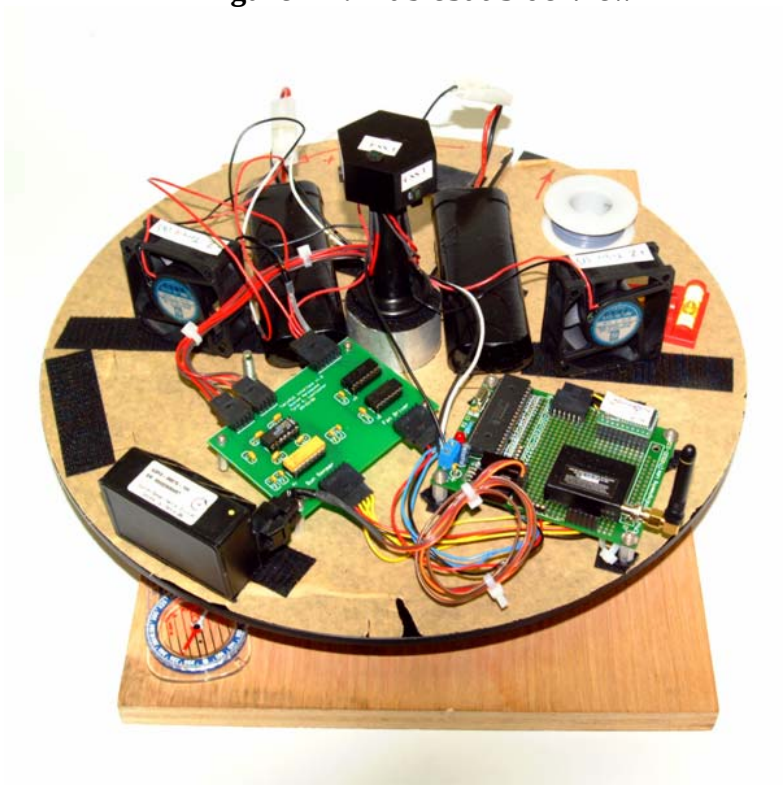

Figure 7-3. TableSat Top View

[Technical contact: Dave Mangus]

8.0 Outreach Activities

8.1 SAMPEX University Operations

The University of Maryland Aerospace Engineering Department completed its third full year of sole responsibility for flight dynamics support of the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) spacecraft. In this role, a team of University of Maryland undergraduate and graduate students provides routine spacecraft orbit determination, attitude determination, attitude sensor analysis, and flight dynamics product generation. This effort is sponsored and supported by the FDAB, which provides consultation support as needed and periodically reviews the overall program status. This has been a very successful outreach initiative and gives the student team practical experience and training in spacecraft flight dynamics computations, the use of several commercial ground support tools and analysis of flight data. As an additional benefit, this program helps give students valuable experience for future employment. One of the new hires in the branch this year (Oscar Hsu) was a member of the student team at Maryland that supported SAMPEX flight dynamics operations.

[Technical Contact: Tom Stengle]

8.2 PREST Program

During FY02, the FDAB supported Nicholas Hamilton (USAF) under a grant with the George Washington University Program of Research and Education in Space Technology (PREST). This student completed his work in residence at the GSFC, which focused on formation flying control approaches.

[Technical Contact: Tom Stengle]

8.3 Graduate Student Research Program (GSRP)

The Graduate Student Researchers program (GSRP) is a program that brings quality graduate students into collaborative research arrangements with NASA scientists and engineers. Entrance into the program is highly competitive and results typically in a three-year commitment by Goddard and the selected students to perform research of mutual interest. In FY02, a total of seven students were sponsored by the FDAB. These students and their research abstracts are listed below:

<u>"Feasibility of Atmospheric Penetration for Satellite Formation Flying Experiment."</u>
<u>Researcher: Joseph Schultz, University of Maryland (third year).</u>
This research develops optimal control and guidance methods needed to maneuver a formation of satellites through penetrations into the upper atmosphere. The research has direct application to NASA's Geospace Electrodynamic Connections (GEC) Mission

where its formation of satellites will be dipping into the upper atmosphere for electric and magnetic field measurements. Of large concern is that the flexibility of large booms on the satellite may cause it to become unstable during the atmospheric portion of flight. This research will determine guidance and control laws that optimize the fuel savings of formation maneuvers during an aeroassist while also preventing satellite instabilities.

" Adaptive Satellite Attitude Control." Researcher: Kevin Walchco, University of Florida (second year).
Attitude control of small spacecraft is a particularly important element in any of Goddard's existing and future missions. Typically designers use classical control due to its simplicity and ease of implementation. However, classical control cannot provide robustness in the presence of disturbances and uncertainties such as solar snap, fuel slosh, and vibrations. One of the most promising robust methods is sliding mode control. In this work, an adaptive sliding mode controller, which utilizes Kalman filtering to estimate dynamic and uncertain parameters in a satellite, is used to improve performance and robustness of the attitude control.

"Investigation of Libration Orbits in the Earth-Moon System." Researcher: Raquel Jarabek, University of Maryland (second year).
Additional uses for libration point orbits are currently being discovered and more satellites will make use of libration points in the future. This creates a need for more automated software to plan trajectories to libration points. To meet this need, an automated method will be developed to find the optimal path for spacecraft trajectories to Sun-Earth libration points. Three-body motion will be simulated through computer programming and the applicable optimal control problem will be formulated using the Hamilton-Jacobi-Bellman equations. The solution to the optimal control problem will be compared to manifold theory to ensure that the optimal path is found.

"Decentralized Control of Distributed Satellite Networks." Researcher: Belanger, UCLA (second year).
Decentralized control of satellite clusters in the context of limited information exchange is studied. Optimal control laws are derived for various communications paradigms, using a combination of static team theory and dynamics programming techniques. These control laws are linear in the local measurement history and the a priori state estimate. One communication paradigm discussed appears to represent the minimal information exchange necessary to sustain an affine control law. These communication paradigms and associated control laws are applied and studied in the context of a high fidelity satellite cluster simulation.

"Trajectory Planning for Coordinating Satellites Using Command Generation." Researcher: Erika Biediger, Georgia Institute of Technology (first year).
The proposed work seeks to enhance the current state-of-the-art formation flying algorithms by utilizing Command Generation, specifically input shaping. Input Shaping is a relatively simple technique that will allow the flexible spacecraft to move without inducing residual vibration, limit transient deflection, and move in a fuel-efficient

manner. The proposed work will develop and employ a real-time pulse generator to address the vibration issues onboard each satellite. The real-time pulse generator will be integrated with the current formation flying algorithms for enhanced performance.

"Synthesis of Attitude Determination Algorithms on a PiVoT GPS Receiver."
Researcher: Jared Madsen, University of Texas at Austin (first year)
This research will combine the carrier wave and signal to noise ratio methods of attitude determination on a PiVoT GPS receiver. To accomplish this synthesis, the carrier wave method of attitude determination must be altered to allow for solutions with canted antennas. A filter will be designed to integrate information from both methods to achieve the best possible solutions. This system will provide solutions even when the integer ambiguity resolution process is unfinished or has failed. It is also anticipated that this new system will have improved integer ambiguity resolution speed. This new system will be accurate and robust.

[Technical Contact: Tom Stengle]

8.4 Mission Design & Navigation Workshop
http://FDAB1.GSFC.NASA.GOV/

The FDAB held a Mission Design and Navigation Workshop on January 9, 2002. It was a very successful event, drawing over 90 registered participants. Branch head Tom Stengle and senior engineer David Folta gave the presentation which covered the FDAB history and business plan, information about and recent accomplishments in each flight regime (LEO, MEO/HEO, GEO, lunar, libration, and interplanetary), and branch technology development efforts. In addition to the presentation, branch members gave hands-on demonstrations of FDAB tools and capabilities. FDAB hopes to sponsor a similar event each year, both to update the mission design and navigation information and also to highlight the branch's work in the attitude determination and control areas.

For a copy of the presentation and to view the posters that were on display, visit the FDAB website listed above and click on the Workshop link.

[Technical contact: Lauri Newman]

Appendix A – Goddard and NASA Awards

Team Awards

NASA Software of the Year Award (SOYA); Code 572/583 and ai-solutions inc. won runner up of the prestigious software of the year competition for "AutoCon - Autonomous Maneuver Control Flight Software". The SOYA is held yearly and involved 8 competitors from each NASA center.

NASA Group Achievement Awards for the EO-1 Project Team and for the EO-1 Formation Flying Team

NASA Group Achievement Award – Microwave Anisotropy Probe (MAP) Guidance, Navigation and Control (GN&C) Team

NASA Group Achievement Award -- Center of Excellence MAP team

Goddard Center of Excellence Award- Triana Project

Special Act Award for the Sun-Earth Connection Roadmap Missions Definition Team

Special Act Award for the NASA GSFC X-43 Mishap Investigation Team

Individual Goddard/NASA level Awards

NASA Exceptional Achievement Award- Aprille Ericsson

Appendix B - University Grants

The following university grants being administered by FDAB engineers were in place in FY02:

1. GRANT NAG5-11839 with **Purdue University** titled "Application of Dynamical System Theory, Control Methods, and Optimization Strategies to Trajectory Design and Mission Analysis Involving Formation Flying at Libration Points for GFSC Missions" This grant was established to investigate the application of dynamical systems to formation flying missions at the Sun-Earth libration points. Investigation involved study of DS applications to traditional non-linear and linear control methods and the use of the natural dynamics regions. The results are being used to design the trajectories of Constellation-X, FKSI, and MAXIM.

   [Technical Contact: David.C.Folta]

2. GRANT NAG5-3587 with **Purdue University** titled "Dynamical System Theory, Numerical Methods, Optimization Strategies, and their Applications to Trajectory Design and Mission Analysis Involving Lissajous and Halo Orbits at the GFSC GNCC" This grant was established to continue Dynamical Systems (DS) applications. Investigation involved further study of DS applications of manifolds, improvements to the Generator utility to include additional information on lunar gravity assist and targeting schemes, investigation of orbit bifurcation of manifolds, and investigation of the use of combinatorics for trajectory design and optimization. The result of this grant was used to design the trajectories of JWST, Triana, Constellation-X, FKSI, and others

   [Technical Contact: David.C.Folta]

3. GRANT NAG5-12228 with **University of Illinois at Urbana Champaign** titled "Advanced Methods For Optimal Trajectory Design" Investigation and development of genetic algorithms and primer vector theory applications to optimization of orbit deign. The UIUC Computational Astrodynamic Research Laboratory (CARL) investigated orbital state transition matrix methods. Several established techniques have been identified. The varying strengths and weaknesses of the methods were established for Gim and Alfriend, Goodyear, Danby, and Battin, Matrix methods for the approximate solution of differential equations are applied to the development of general perturbations in rectangular coordinates. A tutorial session to demonstrate how to use the trajectory analysis software that was co-developed with Spectrum Astro was organized. Sample missions are being sought out to develop into example scenarios in the software. Hopefully this will facilitate the use of the software. The result of this grant was used to minimize the DV and Fuel costs on SDO, GPM, and Leonardo.

   [Technical Contact: David.C.Folta]

4. GRANT NAG5-12119 with **Virginia Tech** titled "Time-Optimal Control for Formation Establishment and Maneuvering" Investigation of time optimal transfer for Low Earth orbits. Investigation focused on time-constrained problems. The results of this grant were used on SDO and LISA.

   [Technical Contact: David.C.Folta]

5. GRANT NAG5-10384 with **University of Cincinnati** titled "Dynamics and Control of Distributed Spacecraft" Investigation of the use of differential solar radiation pressure effects for formation control and establishment. It was applied to the transfer and formation maintenance of Low Earth circular and elliptical orbits. Investigation focused on MMS mission like problems. The results of this grant were used on MMS and Leonardo.

   [Technical Contact: David.C.Folta]

6. GRANT NAG5-9961 with the **University of Maryland** Department of Aerospace Engineering titled "Precise Virtual Rigid Body Control of a Satellite Constellation." This grant is developing a possible control strategy for formation flying.

   [Technical Contact: Thomas Stengle]

7. GRANT NAG5-9890 with the **University of Maryland** Department of Aerospace Engineering titled "Rarefied Flow Aerodynamics for Stability and Control of Formation-Flying Satellites." This grant is researching problems and control strategies for spacecraft flying in formation with low perigee passes. This research may benefit the development of control approaches for the Geospace Electrodynamics Connections (GEC) mission.

   [Technical Contact: Marco Concha]

8. GRANTS NAG5-8694 and NAG5-8879 with the **University of California at Los Angeles** titled "Decentralized Estimation and Control of Distributed Spacecraft," and "Precise Relative State Estimation and Control of Distributed Satellite Networks." These grants are developing and applying new decentralized control architectures for satellite formations.

   [Technical Conract: Russell Carpenter]

9. GRANT NAG5-9829 with the **University of Texas at Austin** titled “Spacecraft Rendezvous Navigation with Integrated INS-GPS.” This grant is focusing on GPS/INS software architecture development for relative navigation and attitude determination.

   [Technical Contact: Russell Carpenter]

10. GRANT NAG5-12179 with **State University of New York Buffalo** and Dr. John Crassidis of the Department of Mechanical and Aerospace Engineering titled “Development of Automated Alignment and Calibration Algorithms”. This grant is studying sensor calibration algorithms which would be suitable for a spacecraft onboard computer.

    [Technical Contact: Richard Harman]

11. GRANT NAG5-11919 with **Cornell University** and Dr. Mark Psiaki of the Sibley School of Mechanical & Aerospace Engineering titled “Euler Dynamics-Based Estimation Algorithms for Spacecraft Attitude and Rate Determination”. This grant looks at accurately estimating spacecraft attitude and rate when no gyros are available.

    [Technical Contact: Richard Harman]

12. GRANT NAG5-11331 with **State University of NY at Buffalo** titled, "Attitude Determination Schemes for the CEGANS Sensor.” The CEGANS concept is to perform spacecraft attitude determination by considering the sightline vectors of GPS SVs visible to each antenna element of a multi-element array fixed to the user spacecraft. Simulation data provided by NASA-Goddard will be analyzed at the University of Buffalo in order to investigate robust and optimal attitude determination schemes for the CEGANS sensor.

    [Technical Contact: David Quinn]

13. GRANT NAG5-10563 with the **University of Maryland** Department of Aerospace Engineering titled "Automation of SAMPEX Orbit Determination." This grant is researching the automation of the orbit determination of the SAMPEX satellite through the automation of the following phases: data acquisition, data processing, and data output.

    [Technical Contact: Joe Toth]

14. GRANT NAG5-12228 with the **University of Illinois Urbana Champaign** Aeronautical and Astronautical Engineering Dept. Entitled "Multi-Function Stochastic Optimization for Space Mission Design". Under this grant, UIUC is developing optimization algorithms for use in matlab. These capabilities will be included into the TrajOpt architecture to be used with existing mission design ools such as FreeFlyer, Astrogator, or GMAT.

    [Technical Contact: Steven Hughes]

15. GRANT NAG5-12312 with the **University of California San Diego** Department of Mathematics Entitled " Software for Constrained Optimization". Under this grant, the UCSC is developing constrained optimization approaches to be included in the TrajOpt software. The TrajOpt software will enable optimal mission design in FreeFlyer, Astrogator, and GMAT.

    [Technical Conact: Steven Hughes]

Appendix C – Conferences and Papers

Given below are abstracts from professional papers and technical presentations that were prepared and delivered in FY02 by branch members.

JOURNAL ARTICLES

IEEE Transactions on Automatic Control, submitted May 2002

" A Coupled Nonlinear Spacecraft Attitude Controller and Observer with an Unknown Constant Gyro Bias and Gyro Noise", Thienel (GSFC), Sanner (University of Maryland)

Abstract: A nonlinear control scheme for attitude control of a spacecraft is combined with a nonlinear gyro bias observer for the case of constant gyro bias. A persistency of excitation analysis shows the observer bias estimates converge to the true bias values exponentially fast. The resulting coupled, closed loop dynamics are proven by a Lyapunov analysis to be globally stable, with asymptotically perfect tracking. The analysis is extended to consider the effects of noise in addition to the gyro bias. A simulation of the proposed observer-controller design is given for a rigid spacecraft tracking a specified, time-varying attitude sequence to illustrate the theoretical claims.

Journal of Guidance, Control, and Dynamics (Published January-February 2002)

"Optimal Fusion of a Given Quaternion with Vector Measurements", Bar-Itzhack (Technion), Harman (GSFC).

ABSTRACT: Several satellites that use devices called autonomous star trackers (ASTs) are presently operating. These devices put out the satellites' attitude in the form of a quaternion. Usually the satellites also carry other attitude measuring devices, such as sun sensors and magnetometers that measure vectors in body coordinates. Although the accuracy of the AST surpasses that of the other sensors, due to the synergistic effect of sensor fusion, it is still desirable to incorporate the measurements of the less accurate sensors in the attitude determination process. The question is, then, how to blend optimally the AST-generated quaternion with vector measurements. This problem rose, for example, in the design of the attitude determination algorithm of the Microwave Anisotropy Probe (MAP) satellite, which was launched on 30 June 2001. MAP has two ASTs and two sun sensors, one of which is more accurate than the other. Although we have two quaternion-generating devices and two vector-measuring sensors, we consider here only one of each. The extension of the solution, proposed here, to multiple devices and multiple sensors, is immediate.

We note that the quaternion is a four-element vector that yields the whole attitude, whereas vector-measuring sensors yield three dimensional vectors each containing only partial information on the attitude. Therefore, we cannot cast the problem of optimal

attitude determination in the form of Wahba's problem.1 That is, we cannot blend quaternions with vector measurements using known algorithms.

If we have more than one simultaneous vector measurement, we can use the vector measurements to, first, find attitude expressed in quaternion form and, then, blend this quaternion with the given one. However, when we have only one vector measurement, this is not possible. Therefore, we need an algorithm that can blend the given quaternion even with one vector measurement.

The algorithm presented here consists of two steps. In the first step, the quaternion is converted into a pair of pseudo vector measurements that express the attitude, and then, in the second step, these pseudo vector measurements, together with the given vector measurement (or measurements), are used as inputs to the *q*-method algorithm,2 which generates the optimal quaternion. The resultant quaternion is optimal in the sense that it is the best . t, in the least squares sense, to all of the vectors.

Journal of Guidance, Control, and Dynamics (Published September-October 2002)

"In-Space Calibration of a Skewed Gyro Quadruplet", Bar-Itzhack (Technion), Harman (GSFC).

ABSTRACT: A new approach to gyro calibration, where the spacecraft dynamics equation, attitude measurements, and the gyro outputs are used in a pseudo linear Kalman filter that estimates the calibration parameters. Also an algorithm is presented for calibrating a skewed quadruplet rather than the customary triad gyro-set aligned along the body coordinate axes. In particular, a new misalignment error model is derived for this case. The new calibration algorithm is applied to the EOS-AQUA satellite gyros. The effectiveness of the new algorithm is demonstrated through simulations.

CONFERENCES

16th International Symposium on Space Flight Dynamics Pasadena, CA, December 3-7, 2001

"Application Of Monte Carlo Analyses For The Microwave Anisotropy Probe (Map) Mission", Mesarch(GSFC), Rohrbaugh, Schiff (aisolutions).

ABSTRACT: The Microwave Anisotropy Probe (MAP) is the third launch in the National Aeronautics and Space Administration's (NASA's) a Medium Class Explorers (MIDEX) program. MAP will measure, in greater detail, the cosmic microwave background radiation from an orbit about the Sun-Earth/Moon Lagrangian point. Maneuvers will be required to transition MAP from its initial highly elliptical orbit to a lunar encounter which will provide the remaining energy to send MAP out to a lissajous orbit about L2. Monte Carlo analysis methods were used to evaluate the potential maneuver error sources and determine their effect of the fixed MAP propellant budget.

This paper will discuss the results of the analyses on three separate phases of the MAP mission recovering from launch vehicle errors, responding to phasing loop maneuver errors, and evaluating the effect of maneuver execution errors and orbit determination errors on stationkeeping maneuvers at L2.

"Trajectory Design for the Microwave Anisotropy Probe (MAP)", Newman (GSFC), Rohrbaugh (a.i. Solutions)

ABSTRACT: The Microwave Anisotropy Probe (MAP) mission orbit is a Lissajous orbit about the L2 Sun-Earth Lagrange point. The trajectory design for MAP is complex, having many requirements that must be met including shadow avoidance, sun angle constraints, lissajous size and shape characteristics, and limited Delta-V budget. The results of the trajectory design analysis are presented. The results show relationships between the requirements and the resulting trajectory in an effort to establish patterns and repeatability in defining satisfactory orbits. The paper discusses the preliminary trade-offs to establish a baseline trajectory, analysis to establish the nominal daily trajectory, and the launch window determination.

"Designing Phase 2 for the Double-Lunar Swingby of the Magnetospheric Multiscale Mission", Edery, Schiff (a.i. solutions)

ABSTRACT The double-lunar swingby (DLS) of the Magnetospheric MultiScale (MMS) mission is required, within a tight delta-V budget of 90 m/s, to change significantly the orbital elements of an initial orbit: to increase dramatically its inclination (by 570), decrease significantly its eccentricity (from 0.96 to 0.66) and keep its semimajor axis approximately constant. We obtain double-lunar swingbys that accomplish this task with a remarkably low delta-V of 50.3 m/s. Our approach is semi-analytical: a derived analytical expression is used to determine that a non-symmetrical targeting scheme is best suited for this problem

IEEE Conference on Decision and Control, Orlando, FL, December 4-7, 2001

"A Coupled Nonlinear Spacecraft Attitude Controller/Observer with an Unknown Constant Gyro Bias", Thienel (GSFC), Sanner (University of Maryland)

ABSTRACT: A nonlinear control scheme for attitude control of a spacecraft is combined with a nonlinear gyro bias observer for the case of constant gyro bias. A persistency of excitation analysis shows the observer bias estimates converge to the true bias values exponentially fast. The resulting coupled, closed loop dynamics are proven by a Lyapunov analysis to be globally stable, with asymptotically perfect tracking. The analysis is extended to consider the effects of noise in addition to the gyro bias. A simulation of the proposed observer-controller design is given for a rigid spacecraft tracking a specified, time-varying attitude sequence to illustrate the theoretical claims.

25th Annual AAS Guidance and Control Conference, Breckenridge, CO, February, 2002

"Preliminary Results of the GPS Flight Experiment on the High Earth Orbit AMSAT-OSCAR 40 Spacecraft", Moreau, Bauer, Carpenter, E. Davis (GSFC), G. Davis (Emergent Space Technologies), Jackson (Orbital Sciences Corporation)

ABSTRACT: The GPS flight experiment on the High Earth Orbit (HEO) AMSAT-OSCAR 40 (AO-40) spacecraft was activated for a period of approximately six weeks between 25 September and 2 November, 2001, and the initial results have exciting implications for using GPS as a low-cost orbit determination sensor for future HEO missions. AO-40, an amateur radio satellite launched November 16, 2000, is currently in a low inclination, 1000 by 58,800 km altitude orbit. Although the GPS receiver was not initialized in any way, it regularly returned GPS observations from points all around the orbit. Raw signal to noise levels as high as 12 AMUs (Trimble Amplitude Measurement Units) or approximately 48 dB Hz have been recorded at apogee, when the spacecraft was close to 60,000 km in altitude. On several occasions when the receiver was below the GPS constellation (below 20,000 km altitude), observations were reported for GPS satellites tracked through side lobe transmissions. Although the receiver has not returned any point solutions, there has been at least one occasion when four satellites were tracked simultaneously, and this short arc of data was used to compute point solutions after the fact. These results are encouraging, especially considering the spacecraft is currently in a spin-stabilized attitude mode that narrows the effective field of view of the receiving antennas and adversely affects GPS tracking. Already AO-40 has demonstrated the feasibility of recording GPS observations in HEO using an unaided receiver. Furthermore, it is providing important information about the characteristics of GPS signals received by a spacecraft in a HEO, which has long been of interest to many in the GPS community. Based on the data returned so far, the tracking performance is expected to improve when the spacecraft is transitioned to a three axis stabilized, nadir pointing attitude in Summer, 2002.

"Microwave Anisotropy Probe (MAP) Launch and Early Operations", O'Donnell, Andrews, Starin, Ward (GSFC)

ABSTRACT: The Microwave Anisotropy Probe (MAP), a follow-on to the Differential Microwave Radiometer (DMR) instrument on the Cosmic Background Explorer (COBE), was launched from the Kennedy Space Center at 19:46:46 UTC on June 30, 2001. The powered flight and separation from the Delta II appeared to go as designed, with the launch placing MAP well within 1σ launch dispersion and with less than 7 Nms of tip-off momentum. Because of this relatively low momentum, MAP was able to acquire the sun within only 15 minutes with a battery state of charge of 94%. After MAP's successful launch, a six week period of in-orbit checkout and orbit maneuvers followed. The dual purpose of the in-orbit checkout period was to validate the correct performance of all of MAP's systems and, from the attitude control system (ACS) point of view, to calibrate the performance of the spacecraft ACS sensors and actuators to maximize system performance. In addition to the checkout activities performed by the MAP team, the other critical activity taking place during the first six weeks after launch were a series of orbit

maneuvers necessary to get the spacecraft from its launch orbit out to its desired orbit about L2, the second Earth-Sun Lagrange point.

As MAP continues its standard operations, its ACS design is meeting all of its requirements to successfully complete the mission. This paper will describe the launch and early operations summarized above in greater detail, and show the performance of the attitude control and attitude determination system versus its requirements. Additionally, some of the unexpected events that occurred during this period will be discussed, including two events which dropped the spacecraft into its Safehold Mode and the presence of an "anomalous force" observed during each of the perigee orbit maneuvers that had the potential to cause these critical maneuvers to be prematurely aborted.

42nd Israel Annual Conference on Aerospace Sciences, February 20-21, 2002, Tel-Aviv -Haifa, Israel

"State-Dependent Pseudo-Linear Filter for Spacecraft Attitude and Rate Estimation", Bar-Itzhack (Technion) ,Harman (GSFC) ,Choukroun (Technion).

ABSTRACT: This paper presents the development and performance of a special algorithm for estimating the attitude and angular rate of a spacecraft. The algorithm is a pseudo-linear Kalman filter, which is an ordinary linear Kalman filter that operates on a linear model whose matrices are current state estimate dependent. The nonlinear rotational dynamics equation of the spacecraft is presented in the state space as a state-dependent linear system. Two types of measurements are considered. One type is a measurement of the quaternion of rotation, which is obtained from a newly introduced star tracker based apparatus. The other type of measurement is that of vectors, which permits the use of a variety of vector measuring sensors like sun sensors and magnetometers. Several measurement models are presented, a linear model for the case where the measured quantity is the quaternion, and two pseudo-linear measurement models when the measured quantities are vectors. In the latter situation, one model is for the case when the attitude is represented by a quaternion and the other is for the case where it is represented by a direction cosine matrix. The state-dependent pseudo linear filter is tested using simulated spacecraft rotations. The efficiency of each case is demonstrated through simulation.

"Optimal Fusion of a Given Quaternion with Vector-Measurements", Bar-Itzhack (Technion), Harman (GSFC).

ABSTRACT: Several satellites that use devices called Autonomous Star Trackers (ASTs) are presently operating. These devices put out the satellites' attitude in the form of a quaternion. Usually the satellites also carry other attitude measuring devices, like sun sensors and magnetometers that measure vectors in body coordinates. Although the accuracy of the AST surpasses that of the other sensors, due to the synergistic effect of sensor fusion, it is still desirable to incorporate the measurements of the less accurate sensors in the attitude determination process. The question is then, how to optimally

blend the AST generated quaternion with vector-measurements. This problem rose, for example, in the design of the attitude determination algorithm of the Microwave Anisotropy Probe (MAP) satellite, which was launched on June 30, 2001. MAP has two ASTs and two sun sensors, one of which is more accurate than the other. Although we have two quaternion-generating devices and two vector-measuring sensors, we consider here only one of each. The extension of the solution, proposed here, to multiple devices and multiple sensors, is immediate.

We note that the quaternion is a four-element vector that yields the whole attitude whereas vector-measuring sensors yield three-dimensional vectors each containing only partial information on the attitude. Therefore we cannot cast the problem of optimal attitude determination in the form of Wahba's Problem [1]. That is, we cannot blend quaternions with vector-measurements using known algorithms.

If we have more than one simultaneous vector-measurement we can use the vector-measurements to, first, find attitude expressed in quaternion form and then blend this quaternion with the given one. However, when we have only one vector-measurement, this is not possible. Therefore we need an algorithm that can blend the given quaternion even with one vector-measurement.

The algorithm presented here consists of two steps. In the first step the quaternion is converted into a pair of pseudo vector-measurements that express the attitude, and then, in the second step, these pseudo vector-measurements, together with the given vector-measurement (or measurements), are used as inputs to the q-Method algorithm [2], which generates the optimal quaternion. The resultant quaternion is optimal in the sense that it is the best fit, in the least squares sense, to all the vectors.

STK Users' Conference, Washington, DC, June 3-4, 2002

"MAP Trajectory Design Using STK", Woodard (GSFC)

ABSTRACT: The NASA Goddard Space Flight Center (GSFC) developed the Microwave Anisotropy Probe (MAP) mission to produce an accurate full-sky map of the cosmic microwave background temperature fluctuations – anisotropy. The MAP mission orbit is a Lissajous orbit about the Sun-Earth L2 Lagrange Point. The mission duration is approximately 27 months with 3 to 4 months of transfer time to the final mission orbit about L2. The mission is exceptional from a trajectory perspective because it is the first mission to orbit the Sun-Earth L2 Lagrange Point.

MAP was launched on June 30, 2001 into a highly elliptical Earth orbit with a 28.7° inclination. In the following weeks, the GSFC trajectory design team planned and executed a sequence of phasing loops and performed a lunar gravity assist to reach the final mission orbit about the Sun-Earth L2 Lagrange point. MAP used a lunar swingby strategy since it reduced the fuel required to achieve the desired Lissajous orbit.

The trajectory team used STK and its Astrogator module to assist in nearly all aspects of trajectory maneuver planning and execution. This included performing prelaunch trajectory analyses, computing delta-V budgets, verifying mission orbital constraints, providing Detailed Trajectory Objective (DTO) analyses to the launch vehicle team, defining launch windows, performing contingency analyses, and on-orbit maneuver planning and verification. To accomplish these tasks, the trajectory team defined several mission-specific Astrogator objects, and created several Matlab scripts that use the STK Connect interface to automate repetitive tasks.

SPIE Astronomical Telescopes and Instrumentation Conference, 22-28 August 2002

"Formation Control for the MAXIM and MAXIM Pathfinder Missions", Luquette, Leitner (GSFC), Gendreau, Sanner (University of Maryland)

ABSTRACT: Over the next twenty years, a wave of change is occurring in the space-based scientific remote sensing community. While the fundamental limits in the spatial and angular resolution achievable in spacecraft have been reached, based on today's technology, an expansive new technology base has appeared over the past decade in the area of Distributed Space Systems (DSS). A key subset of the DSS technology area is that which covers precision formation flying of space vehicles. Through precision formation flying, the baselines, previously defined by the largest monolithic structure which could fit in the largest launch vehicle fairing, are now virtually unlimited. Several missions including the Micro-Arcsecond X-ray Imaging Mission (MAXIM) [1], the associated MAXIM Pathfinder mission [2], and the Stellar Imager will drive the formation flying challenges to achieve unprecedented baselines for high resolution, extended-scene, interferometry in the ultraviolet and X-ray regimes. This paper focuses on establishing the feasibility for the formation control of the MAXIM Pathfinder mission (which will involve seven spacecraft flying in formation). The MAXIM mission (which involves over thirty spacecraft flying in formation) is also discussed. The Stellar Imager mission requirements are on the same order of those for MAXIM. This paper specifically addresses: (1) high-level science requirements for these missions and how they evolve into engineering requirements; (2) the formation control architecture devised for such missions; (3) the design of the formation control laws to maintain very high precision relative positions; and (4) the levels of fuel usage required in the duration of these missions. Specific preliminary results are presented for one formulation of the MAXIM pathfinder mission.

Libration Point Orbits and Applications, Parador d'Aiguablava, Girona, Spain10 - 14 June, 2002

"Orbit Determination Issues for Libration Point Orbits", Beckman (GSFC)

ABSTRACT: Libration point mission designers require knowledge of orbital accuracy for a variety of analyses including station keeping control strategies, transfer trajectory

design, and formation and constellation control. Past publications have detailed orbit determination (OD) results from individual libration point missions. This paper collects both published and unpublished results from four previous libration point missions (ISEE-3, SOHO, ACE and MAP) supported by Goddard Space Flight Center's Guidance, Navigation & Control Center. The results of those missions are presented along with OD issues specific to each mission. All past missions have been limited to ground based tracking through NASA ground sites using standard range and Doppler measurement types. Advanced technology is enabling other OD options including onboard navigation using onboard attitude sensors and the use of the Very Long Baseline Interferometry (VLBI) measurement Delta Differenced One-Way Range (DDOR). Both options potentially enable missions to reduce coherent dedicated tracking passes while maintaining orbital accuracy. With the increased projected loading of the DSN, missions must find alternatives to the standard OD scenario.

"Libration Orbit Mission Design: Applications Of Numerical And Dynamical Methods", Folta, Beckman (GSFC)

ABSTRACT: Sun-Earth libration point orbits serve as excellent locations for scientific investigations. These orbits are often selected to minimize environmental disturbances and maximize observing efficiency. Trajectory design in support of libration orbits is ever more challenging as more complex missions are envisioned in the next decade. Trajectory design software must be further enabled to incorporate better understanding of the libration orbit solution space and thus improve the efficiency and expand the capabilities of current approaches.
The Goddard Space Flight Center (GSFC) is currently supporting multiple libration missions. This end-to-end support consists of mission operations, trajectory design, and control. It also includes algorithm and software development of applications. The recently launched Microwave Anisotropy Probe (MAP) and upcoming Next Generation Space Telescope (NGST) and Constellation-X missions are examples of the use of improved numerical methods for attaining constrained orbits parameters and controlling their dynamical evolution at the collinear libration points. This paper presents a history of libration point missions, a brief description of the numerical and dynamical design techniques including software used, and a sample of GSFC future mission designs.

AIAA Guidance, Navigation, and Controls Conf., Monterrey, CA, August 5-8, 2002

"MAP Attitude Control System Design and Flight Performance", Andrews, O'Donnell (GSFC)

ABSTRACT: The Microwave Anisotropy Probe (MAP) is a follow-on to the Differential Microwave Radiometer (DMR) instrument on the Cosmic Background Explorer (COBE) spacecraft. To make a full-sky map of cosmic microwave background fluctuations, a combination fast spin and slow precession motion is used that will cover the entire celestial sphere in six months. These rates and the sunline angle are tightly controlled to generate the full sky map. Sufficient attitude knowledge is provided to yield instrument

pointing to a standard deviation (1-sigma) of 1.3 arc-minutes per axis. In addition, the spacecraft acquires and holds the sunline at initial acquisition, and in the event of a failure. Finally, the spacecraft slews to the proper orbit adjust orientations and to the proper off-sunline attitude to start the compound spin. The design and flight performance of the reaction wheel based control modes and attitude determination system will be discussed. Flight results will be shown for comparison to system requirements.

"Recent Flight Results of the Trmm Kalman Filter", Andrews (GSFC), Bilanow (SAIC)

ABSTRACT: The Tropical Rainfall Measuring Mission (TRMM) spacecraft is a nadir pointing spacecraft that nominally controlled the roll and pitch attitude based on the Earth Sensor Assembly (ESA) output. TRMM's nominal orbit altitude was 350 km, until raised to 402 km to prolong mission life. During the boost, the ESA experienced a decreasing signal to noise ratio, until sun interference at 383 km altitude made the ESA data unreliable for attitude determination. At that point, the backup attitude determination algorithm, an extended Kalman filter, was enabled. After the boost finished, TRMM reacquired its nadir-pointing attitude, and continued its mission. This paper will briefly discuss the boost and the decision to turn on the backup attitude determination algorithm. A description of the extended Kalman filter algorithm will be given. In addition, flight results from analyzing attitude data and the results of software changes made onboard TRMM will be discussed. Some lessons learned are presented.

"Partially Decentralized Control Architectures For Satellite Formations", Carpenter (GSFC)

ABSTRACT: In a partially decentralized control architecture, more than one but less than all nodes have supervisory capability. This paper describes an approach to choosing the number of supervisors in such an architecture, based on a reliability vs. cost trade. It also considers the implications of these results for the design of navigation systems for satellite formations that could be controlled with a partially decentralized architecture. Using an assumed cost model, analytic and simulation-based results indicate that it may be cheaper to achieve a given overall system reliability with a partially decentralized architecture containing only a few supervisors, than with either fully decentralized or purely centralized architectures. Nominally, the subset of supervisors may act as centralized estimation and control nodes for corresponding subsets of the remaining subordinate nodes, processing all the measurement data from all their subordinates, or fusing the subordinates' local estimates with a scheme that compensates for correlations among the local states estimates. The supervisors may then act as decentralized estimation and control peers with respect to each other. However, if the state estimates of each spacecraft are uncorrelated, the supervisors may command globally optimal maneuvers derived from simple differencing of the subordinates' local estimates. Since the absolute positions and velocities of each spacecraft are unique, correlations may only occur through common biases, common process noise, or indirectly through common model errors. A simple example illustrates the discussion on the role of correlation.

"A Convex Approach to Fault Tolerant Control", Maghami (GSFC), Cox (NASA LaRC)

ABSTRACT: The design of control laws for dynamic systems with the potential for actuator failures is considered in this work. The use of Linear Matrix Inequalities allows more freedom in controller design criteria than typically available with robust control. This work proposes an extension of fault-scheduled control design techniques that can find a fixed controller with provable performance over a set of plants. Through convexity of the objective function, performance bounds on this set of plants implies performance bounds on a range of systems defined by a convex hull. This is used to incorporate performance bounds for a variety of soft and hard failures into the control design problem.

"GPS-Based Navigation and Orbit Determination for the AMSAT AO-40 Satellite", G. Davis (Emergent Space Technologies), Moreau, Carpenter, Bauer (GSFC)

ABSTRACT: The AMSAT OSCAR-40 (AO-40) spacecraft occupies a highly elliptical orbit (HEO) to support amateur radio experiments. An interesting aspect of the mission is the attempted use of GPS for navigation and attitude determination in HEO. Previous experiences with GPS tracking in such orbits have demonstrated the ability to acquire GPS signals, but very little data were produced for navigation and orbit determination studies. The AO-40 spacecraft, flying two Trimble Advanced Navigation Sensor (TANS) Vector GPS receivers for signal reception at apogee and at perigee, is the first to demonstrate autonomous tracking of GPS signals from within a HEO with no interaction from ground controllers. Moreover, over 11 weeks of total operations as of June 2002, the receiver has returned a continuous stream of code phase, Doppler, and carrier phase measurements useful for studying GPS signal characteristics and performing post-processed orbit determination studies in HEO. This paper presents the initial efforts to generate AO-40 navigation solutions from pseudorange data reconstructed from the TANS Vector code phase, as well as to generate a precise orbit solution for the AO 40 spacecraft using a batch filter.

"Restoring Redundancy to the MAP Propulsion System", O'Donnell, Davis, Ward (GSFC)

ABSTRACT: The Microwave Anisotropy Probe is a follow-on to the Differential Microwave Radiometer instrument on the Cosmic Background Explorer. Sixteen months before launch, it was discovered that from the time of the critical design review, configuration changes had resulted in a significant migration of the spacecraft's center of mass. As a result, the spacecraft no longer had a viable backup control mode in the event of a failure of the negative pitch axis thruster. Potential solutions to this problem were identified, such as adding thruster plume shields to redirect thruster torque, adding mass to, or removing it from, the spacecraft, adding an additional thruster, moving thrusters, bending thrusters (either nozzles or propellant tubing), or accepting the loss of redundancy for the thruster. The impacts of each solution—including effects on the mass, cost, and fuel budgets, as well as schedule—were considered, and it was decided to bend

the thruster propellant tubing of the two roll control thrusters, allowing that pair to be used for backup control in the negative pitch axis. This paper discusses the problem and the potential solutions, and documents the hardware and software changes that needed to be made to implement the chosen solution. Flight data is presented to show the propulsion system on-orbit performance.

"The Microwave Anisotropy Probe (MAP) Mission", Markley, Andrews, O'Donnell, Ward (GSFC)

ABSTRACT: The Microwave Anisotropy Probe mission is designed to produce a map of the cosmic microwave background radiation over the entire celestial sphere by executing a fast spin and a slow precession of its spin axis about the Sun line to obtain a highly interconnected set of measurements. The spacecraft attitude is sensed and controlled using an inertial reference unit, two star trackers, a digital sun sensor, twelve coarse sun sensors, three reaction wheel assemblies, and a propulsion system. This paper presents an overview of the design of the attitude control system to carry out this mission and presents some early flight experience.

"The Microwave Anisotropy Probe Guidance, Navigation, and Control Hardware Suite", Ward, Davis, O'Donnell (GSFC)

ABSTRACT: In order to meet the complex attitude determination and control requirements of the Microwave Anisotropy Probe (MAP) mission, a diverse set of components was used. The set included two Lockheed Martin AST-201 star trackers, two Kearfott Two-Axis Rate Assemblies mounted to provide X, Y and redundant Z-axis rates, two Adcole Digital Sun Sensor heads sharing one set of electronics, twelve Adcole Coarse Sun Sensor eyes, three Ithaco E-sized Reaction Wheel Assemblies, a Propulsion Subsystem that employed eight Primex Rocket Engine Modules, and a pair of GSFC-designed Attitude Control Electronics to connect all of the components to the spacecraft processor. The on-orbit success of the MAP Guidance, Navigation, and Control System can partially be attributed to the performance of this hardware suite, in addition to the successful algorithm and software design work of the MAP project team. The performance of this hardware is documented, as are some of the spacecraft accommodations and lessons learned that came from working with this particular set of hardware.

"Development of a Two-Wheel Contingency Mode for the MAP Spacecraft", Starin, O'Donnell (GSFC)

ABSTRACT: Microwave Anisotropy Probe (MAP) is a follow-on mission to the Cosmic Background Explorer (COBE), and is currently collecting data from its orbit near the second Sun-Earth libration point. Due to limited mass, power, and financial resources, a traditional reliability concept including fully redundant components was not feasible for MAP. Instead, the MAP design employs selective hardware redundancy in tandem with contingency software modes and algorithms to improve the odds of mission success. One direction for such improvement has been the development of a two-wheel backup control strategy. This strategy would allow MAP to position itself for maneuvers and collect

science data should one of its three reaction wheels fail. Along with operational considerations, the strategy includes three new control algorithms. These algorithms would use the remaining attitude control actuators—thrusters and two reaction wheels—in ways that would achieve control goals while minimizing adverse impacts on the functionality of other subsystems and software.

"An Anomalous Force on the MAP Spacecraft", Starin, O'Donnell, Ward, Wollack (GSFC), Bay (Jackson & Tull), Fink (CSC)

ABSTRACT: The Microwave Anisotropy Probe (MAP) orbits the second Earth-Sun libration point (L_2)—about 1.5 million kilometers outside Earth's orbit—mapping cosmic microwave background radiation. To achieve orbit near L_2 on a small fuel budget, the MAP spacecraft needed to swing past the Moon for a gravity assist. Timing the lunar swing-by required MAP to travel in three high-eccentricity phasing loops with critical maneuvers at a minimum of two, but nominally all three, of the perigee passes. On the approach to the first perigee maneuver, MAP telemetry showed a considerable change in system angular momentum that threatened to cause on-board Failure Detection and Correction (FDC) to abort the critical maneuver. Fortunately, the system momentum did not reach the FDC limit; however, the MAP team did develop a contingency strategy should a stronger anomaly occur before or during subsequent perigee maneuvers. Simultaneously, members of the MAP team developed and tested various hypotheses for the cause of the anomalous force. The final hypothesis was that water was outgassing from the thermal blanketing and freezing to the cold side of the solar shield. As radiation from Earth warmed the cold side of the spacecraft, the uneven sublimation of frozen water created a torque on the spacecraft.

"State-Dependent Pseudo-Linear Filters for Spacecraft Attitude and Rate Estimation", Bar-Itzhack (Technion), Harman (GSFC), Choukroun (Technion)

ABSTRACT: This paper presents the development and performance of a special algorithm for estimating the attitude and angular rate of a spacecraft. The algorithm is a pseudo-linear Kalman filter, which is an ordinary linear Kalman filter that operates on a linear model whose matrices are current state estimate dependent. The nonlinear rotational dynamics equation of the spacecraft is presented in the state space as a state-dependent linear system. Two types of measurements are considered; one type is a measurement of the quaternion of rotation, which is obtained from a newly introduced star tracker based apparatus. The other type of measurement is that of vectors, which permits the use of a variety of vector measuring sensors like sun sensors and magnetometers. Several measurement models are presented, a linear model for the case where the measured quantity is the quaternion, and two measurement models, one of which is pseudo-linear, when the measured quantities are vectors. In the latter situation, one model is for the case where the attitude is represented by a quaternion, and the other is for the is introduced for the latter case. The state-dependent pseudo-linear filter is tested using simulated spacecraft rotations. case where it is represented by a direction cosine matrix. A special observability enhancement algorithm is introduced for the latter

case. The state-dependent pseudo-linear filter is tested using simulated spacecraft rotations.

"An Algorithm for Optimal Fusion of Quaternions with Vector-Measurements", Bar-Itzhack (Technion), Harman (GSFC).

ABSTRACT: This paper presents an algorithm for optimal blending of two sources of attitude information. One source is the attitude quaternion, which fully represents attitude, and the other source is a vector measurement, which contains only partial information on the attitude. When the two sources, which are of a different nature, are mixed properly, the resultant attitude information is superior to that contained in either one of the sources. Monte-Carlo simulations are used to demonstrate the algorithm presented in the paper.

AIAA/AAS Astrodynamics Specialist Conference, Monterey, CA August 5-8, 2002

"Formation Flying Satellite Control Around The L2 Sun-Earth Libration Point", Hamilton (United States Air Force), Folta, Carpenter (GSFC)

ABSTRACT: This paper discusses the development of a linear control algorithm for formations in the vicinity of the L2 sun-Earth libration point. The development of a simplified extended Kalman filter is included as well. Simulations are created for the analysis of the stationkeeping and various formation maneuvers of the Stellar Imager mission. The simulations provide tracking error, estimation error, and control effort results. For formation maneuvering, the formation spacecraft track to within 4 meters of their desired position and within 1.5 millimeters per second of their desired zero velocity. The filter, with few exceptions, keeps the estimation errors within their three-sigma values. Without noise, the controller performs extremely well, with the formation spacecraft tracking to within several micrometers. Each spacecraft uses around 1 to 2 grams of propellant per maneuver, depending on the circumstances.

"Results Of NASA's First Autonomous Formation Flying Experiment: Earth Observing-1 (EO-1)", Folta (GSFC), Hawkins (ai solutions)

ABSTRACT: NASA's first autonomous formation flying mission completed its primary goal of demonstrating an advanced technology called enhanced formation flying. To enable this technology, the Flight Dynamics Analysis Branch at the Goddard Space Flight Center implemented a universal 3-axis formation flying algorithm in an autonomous executive flight code onboard the New Millennium Program's (NMP) Earth Observing-1 (EO-1) spacecraft. This paper describes the mathematical background of the autonomous formation flying algorithm, the onboard flight design and the validation results of this unique system. Results from fully autonomous maneuver control are presented as comparisons between the onboard EO-1 operational autonomous control system called AutoCon™, its ground-based predecessor used in operations, and the

original standalone algorithm. Maneuvers discussed encompass reactionary, routine formation maintenance, and inclination control. Orbital data is also examined to verify that all formation flying requirements were met.

"An Overview of Trajectory Design Operations for the Microwave Anisotropy Probe Mission", Cuevas, Newman, Mesarch, Woodard (GSFC).

ABSTRACT: The purpose of this paper is to document the results of the pre-launch trajectory design and the real-time operations for the Microwave Anisotropy Probe (MAP) mission, launched on June 30, 2001. Once MAP was successfully inserted into a highly elliptical phasing orbit, three perigee maneuvers and a final perigee correction maneuver were performed to tailor a lunar encounter on July 30, 2001. MAP achieved its final Lissajous orbit (0.5° by 10.5°) about the Sun-Earth/Moon L2 libration point via this lunar encounter. This paper will show the maneuvers that were designed to arrive at the mission orbit. A further discussion of how the MAP trajectory analysts altered the pre-launch phasing loop maneuvers as well as the lunar encounter to meet all mission constraints, including the constraint of zero lunar shadows is also included.

"The Maneuver Planning Process For The Microwave Anisotropy Probe (Map) Mission", Mesarch, Andrews (GSFC).

ABSTRACT: The Microwave Anisotropy Probe (MAP) mission utilized a strategy combining highly eccentric phasing loops with a lunar gravity assist to provide a zero-cost insertion into a Lissajous orbit about the Sun-Earth/Moon L2 point. Maneuvers were executed at the phasing loop perigees to correct for launch vehicle errors and to target the lunar gravity assist so that a suitable orbit at L2 was achieved. This paper will discuss the maneuver planning process for designing, verifying, and executing MAP's maneuvers. This paper will also describe how commercial off-the-shelf (COTS) tools were used to execute these tasks and produce a command sequence ready for upload to the spacecraft. These COTS tools included Satellite Tool Kit, MATLAB, and Matrix-X.

"Contingency Planning for the Microwave Anisotropy Probe Mission", Mesarch (GSFC), Rohrbaugh, Schiff (ai solutions)

ABSTRACT: The Microwave Anisotropy Probe (MAP) utilized a phasing loop/lunar encounter strategy to achieve a small amplitude Lissajous orbit about the Sun-Earth/Moon L2 libration point. The use of phasing loops was key in minimizing MAP's overall ΔV needs while also providing ample opportunities for contingency resolution. This paper will discuss the different contingencies and responses studied for MAP. These contingencies included accommodating excessive launch vehicle errors (beyond 3σ), splitting perigee maneuvers to achieve ground station coverage through the Deep Space Network (DSN), delaying the start of a perigee maneuver, aborting a perigee maneuver in the middle of execution, missing a perigee maneuver altogether, and missing the lunar encounter (crucial to achieving the final Lissajous orbit). It is determined that using a phasing loop approach permits many opportunities to correct for a majority of these contingencies.

"*Preliminary Optimal Orbit Design For The LaserInterferometer Space Antenna (LISA)" Hughes (GSFC)*

ABSTRACT: In this paper we present a preliminary optimal orbit analysis for the Laser Interferometer Space Antenna (LISA). LISA is a NASA/ESA mission to study gravitational waves and test predictions of general relativity. The nominal formation consists of three spacecraft in heliocentric orbits at 1 AU and trailing the Earth by twenty degrees. This configuration was chosen as a trade off to reduce the noise sources that will affect the instrument and to reduce the fuel to achieve the final orbit. We present equations for the nominal orbit design (Folkner 97) and discuss several different measures of performance for the LISA formation. All of the measures directly relate the formation dynamics to science performance. Also, constraints on the formation dynamics due to spacecraft and instrument limitations are discussed. Using the nominal solution as an initial guess, the formation is optimized using Sequential Quadratic Programming to maximize the performance while satisfying a set of nonlinear constraints. Results are presented for each of the performance measures.

"On the Singularity in the Estimation of the Quaternion-of-Rotation", Thienel (GSFC), Bar-Itzhack (Technion)

ABSTRACT: It has been claimed in the archival literature that the covariance matrix of a Kalman filter, which is designed to estimate the quaternion-of-rotation, is necessarily rank deficient because the normality constraint of the quaternion produces dependence between the quaternion elements. In reality, though, this phenomenon does not occur. The covariance matrix is not singular, and the filter is well behaved. Several simple examples are presented that demonstrate the regularity of the covariance matrix. First, a Kalman filter is designed to estimate variables subject to a functional relationship. Then the particular problem of quaternion estimation is analyzed. It is shown that the discrepancy stems from the fact that the functional relationship exists between the elements of the quaternion but not between its estimated elements.

ION GPS 2002, September 24-27, 2002, Portland, OR

"Results from the GPS Flight Experiment on the High Earth Orbit AMSAT OSCAR-40 Spacecraft", Moreau, E. Davis, Carpenter (GSFC), Kelbel (Computer Sciences Corporation), G. Davis (Emergent Space Technologies), Axelrad (University of Colorado)

ABSTRACT: A GPS receiver flying on the High Earth Orbit (HEO) AMSAT-OSCAR 40 (AO 40) spacecraft has been returning GPS observations from high above the altitude of the GPS constellation. AO 40, an amateur radio satellite launched November 16, 2000, is currently in a low inclination, 1000 by 59000 km altitude orbit. This low-cost

experiment utilizes a mid 1990's era, 6-channel, C/A code receiver configured with high gain receiving antennas for tracking above the GPS constellation. The receiver has performed well, despite operating significantly outside of its original design environment. It has regularly returned GPS observations from points all around the orbit, with over ten weeks of GPS tracking data collected to date. Signal to noise levels as high as 48 dB Hz have been recorded near apogee, when the spacecraft was at an altitude of close to 60000 km. GPS side lobe signals have been tracked on several occasions, primarily from Block IIR GPS satellites. Although the receiver has not computed a solution in real-time, point solutions have been computed on the ground using simultaneous measurements from four satellites. This experiment has provided important experience dealing with the many challenges inherent to GPS tracking at high altitudes, and the measurements returned are providing valuable information about the characteristics of GPS signals available for future HEO users.

CONFERENCE PRESENTATIONS

NTA National Conference, Las Vegas, NV,
"Guidance, Navigation & Control Innovations at the NASA Goddard Space Flight Center", Dr. A. Ericsson

Appendix D- Acronyms and Abbreviations

This appendix gives the definitions of acronyms used in this document.

AAS	American Astronautical Society
ACE	Attitude Control Electronics
ACS	Attitude Control System
AETD	Applied Engineering and Technology Directorate
AGI	Analytical Graphics, Inc.
AIAA	American Institute of Aeronautics and Astronautics
AKM	Apogee Kick Motor
APL	Applied Physics Laboratory
ATS	Absolute Time Sequence
AU	Astronomical Unit
AUTOFDS	Autonomous Flight Dynamics System
BRDF	Bi-directional Reflectance Distribution Function
BSS	Boeing Satellite Systems
CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial Off-the-Shelf
DFC	Drag Free Control
DoD	Department of Defense
DOF	Degree of Freedom
DRS	Disturbance Reduction System
DSC	Deep Space Calibration
DSN	Deep Space Network
DSS	Distributed Space System
DST	Dynamical Systems Theory
EFF	Enhanced Formation Flying
EKF	Extended Kalman Filter
EM	Expectation Maximization
EO	Earth Observing
EOS	Earth Observing System
EPGM	EOS Polar Ground Network
EPM	Earth Point Mode
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESE	Earth Science Enterprise
ESTO	Earth Science Technology Office
FD	Flight Dynamics
FDAB	Flight Dynamics Analysis Branch
FDC	Fault Detection Correction
FDF	Flight Dynamics Facility
FDT	Flight Dynamics Team
FFTB	Formation Flying Test Bed
FPM	Fine Point Mode
FOT	Flight Operations Team

FSW	Flight Software
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	Fiscal Year
GA	Genetic Algorithm
GALEX	Galaxy Evolution Explorer
GEC	Geospace Electrodynamic Connections
GEO	Geosynchronous Earth Orbit
GEODE	GPS Enhanced Orbit Determination Experiment
GEONS	GPS-Enhanced Orbit Navigation System
GMSEC	Goddard Mission Services Evolution Center
GN&C	Guidance, Navigation and Control
GNC	Guidance, Navigation and Control
GNCD	Guidance, Navigation, and Control Division
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Mission
GPS	Global Positioning Satellite
GRS	Gravity Reference Sensor
GSFC	Goddard Space Flight Center
GSRP	Graduate Student Research Program
GTDS	Goddard Trajectory Determination System
GTO	Geostationary Transfer Orbit
GUI	Graphics User Interface
GUS	Gyroscopic Upper Stage
HEO	High Earth Orbit/ Highly Elliptical Orbit
HGA	High Gain Antenna
HRG	Hemispherical Resonator Gyro
HTML	HyperText Markup Language
I&T	Integration and Test
ICD	Interface Control Document
IMDC	Integrated Mission Design Center
IMU	Inertial Measurement Unit
INCA	Interactive Controls Analysis
ITAR	International Traffic In Arms Regulation
JPL	Jet Propulsion Laboratory
L&EO	Launch and Early Orbit
LAQ	Liquid Apogee Motor
LEO	Low Earth Orbit
LISA	Laser Interferometric Space Antenna
LPT	Low Power Transceiver
LQG	Linear Quadratic Gaussian
LSE	Lunar Science Explorer
MAGNAV	Magnetometer Navigation
MAP	Microwave Anisotropy Probe
MAXIM	Micro-Arcsecond X-ray Imaging Mission
MC	Master Catalog
MCC	Mid Course Correction

Mi	Instrumental Magnitude
MLT	Mean Local Time
MMS	Magnetic Multi-scale Mission
MMSE	Minimum Mean Squared Estimate
MMSCAT	Multi-Mission Star Catalog
MOC	Mission Operations Center
Mv	Visual Magnitude
NASA	National Aeronautical and Space Administration
NGST	Next Generation Space Telescope
NOAA	National Oceanic and Atmospherics Administration
OSC	Orbital Sciences Corporation
OD	Orbit Determination
PC	Personal Computer
PD	Proportional Derivative
PI	Principal Investigator
PM	Proof Mass
POR	Power On Reset
PR	Precipitation Radar
PREST	Program of Research and Education in Space Technology
R&D	Research and Development
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Root-Mean-Square
RSDO	Rapid Spacecraft Development Office
RTADS	Real Time Attitude Determination System
RXTE	Rossi X-Ray Timing Explorer
SADA	Solar Array Drive Assembly
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SAM	Scan Angle Monitor
SDO	Solar Dynamics Observatory
SET	Single Event Transient
SIGI	Space Integrated Global Position System Inertial Navigation System
SK	Stationkeeping
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SOMO	Space Operations Management Office
SPM	Sun Point Mode
SPS	Standard Positioning Service
SSE	Space Science Enterprise
ST	Space Technology
STP	Solar Terrestrial Probe
TAM	Three Axis Magnetometer
TDRSS	Tracking Data Relay Satellite System
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission

URL	Uniform Resource Locator
USGS	United States Geological Survey
USN	Universal Space Network
USNO	United States Naval Observatory
VESPER	Venus Sounder for Planetary Exploration
WIRE	Wide-Field Infrared Explorer
WRS	World Reference System
WSB	Weak Stability Boundary
WWW	World Wide Web